THE THERMAL INSULATION OF STRUCTURES

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BY

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FOREWORD

INSULATION is a subject of prime importance to the refrigerating engineer, and consequently a small treatise by one having a wide experience in this field is very welcome.

The author stresses the importance of measuring the thermal conductivities of the various insulators by using a standardized form of apparatus, since conductivity measurements on very poor heat conductors are not easy to make and attention to detail is essential if reliable data are to be obtained.

This volume is written by a practical man and hence should prove of value to the young engineer entering this branch of engineering.

EZER GRIFFITHS.

PREFACE

In presenting this treatise I have endeavoured to simplify the matter discussed in order to avoid complications with which the practical reader need not be concerned. The criticism may be raised that such simplification necessarily results in the omission of much relevant matter, as, for example, in connection with problems arising from solar radiation and isothermals below ground. But the practical engineer is fortunate, perhaps, in not finding it necessary to make provision for the various sinuations of the geophysical phenomena which affect his work, and is concerned only with a permanent arrangement of plant which will be capable of contending with peak conditions as required.

Similarly, the figures of test results recorded herein have been confined almost entirely to those due to the National Physical Laboratory and to the methods of test devised by that authority. The advantage of a standard method of test, details of which are available to the student, will be obvious. This limitation of reference must not be taken as imputing unreliability to the numerous test results emanating from other sources, which have been published from time to time. The engineer who has available a certain insulating material, but is unable to identify it as the subject of a test of which published figures in his possession *might* be a record, is not in a position to place reliance on his data.

In discussing the subject of constant-temperature buildings, it is hardly possible to avoid preponderating reference to those maintained at temperatures below normal. Not only are they in the majority in number, but in addition the exigencies of their service are greater. Yet the same

theoretical considerations are fundamental to every problem of temperature-control, whether the particular temperature desired is higher or lower than that of the atmosphere.

In the field of the domestic type of building, more attention is likely to be accorded to the matter of temperature-control in the future than has been the case up to the present. There is wide scope for improvement in amenities which are common to all, when the courage can be summoned to depart—if only in small degree—from traditional methods of construction and design.

I am indebted to the Controller of H.M. Stationery Office for his kind permission to reproduce test results and other matter from various official publications issued by the Department of Scientific and Industrial Research and by the Air Ministry.

I am indebted also to the British Standards Institution for permission to refer to their publications, and to the Cork Information and Research Bureau for the reproduction of a graph. Finally, I desire to express my thanks to Dr. Ezer Griffiths for his kindness in reading the script.

G. YATE PITTS.

August, 1941.

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CHAPTER I

INSULATION

It may not be out of place to refer at the outset to a misconception which prevails in connection with Thermal Insulation. Possibly this has its origin in some simple matter such as domestic water supply, in which it has long been customary to distinguish between the services by inscribing the words "Hot" and "Cold" on the taps. When water is drawn from one tap, it feels hot to the touch because its temperature is higher than that of the human body, and when drawn from the other it feels cold to the touch because its temperature is lower. Wherever difference of temperature exists between two bodies, heat tends to flow from the body at the higher temperature to the body at the lower, and continues to flow in an endeavour to effect a redistribution of heat such that both bodies will be at the same temperature. There is no such thing as transfer of "cold" from the cold water to the human body, but there is transfer of heat in the reverse direction. The adjective "cold" implies merely a relative condition, and it is an erroneous conception which contemplates cold as being the antithesis of heat.

It is possible by artificial means to frustrate partially this process of temperature equalization, either by continuing to supply heat to the body at the higher temperature or by continuing to extract heat from the body at the lower temperature. This is what occurs in the operation of a hot-room and of a cold-room respectively. A hot-room is required to be at a temperature higher than that of the atmosphere and is rejecting heat all the time from its boundaries to the air in contact with them. Similarly a

cold-room is receiving heat. The artificial devices required to compensate for this heat transfer involve the introduction into the room of some other body at some other temperature, so that heat will flow from or to this body at a rate comparable with that of heat rejection or reception by the boundaries. This quantity of heat is referred to as the "insulation loss." However efficient the insulation may be, there will always be some residual heat flow, since no means exist of preventing it entirely.

Methods.—The heating or cooling element usually takes the form of a system of piping through which is circulated steam or hot water in the case of a hot room, and brine or a refrigerant in the case of a cold-room. Alternative methods include electrical means in the one case, and in the other case the introduction of some substance such as ice, which is capable of absorbing heat, as latent heat of liquefaction, without alteration of temperature. The purpose to which the room is to be put, and the particular process to be pursued in it, involve a heat duty which varies widely. The insulation loss therefore may represent only a small proportion of the total duty, as in a quick-freezing room, or it may represent almost the whole duty, as in a store for the keeping of ice. The heat plant must be of a capacity adequate to cope with the sum of the floating and the standing duties, but it is in the control of the standing duty that the purpose of insulation lies. The standing duty normally is inconstant, and it is necessary to design details of insulation around the maximum reached by the insulation loss in order to ensure the necessary constancy of temperature.

The object of insulating a room is usually the maintenance of some constant temperature. This may or may not be far removed from the average atmospheric temperature in the vicinity, which varies throughout the year, and the actual temperature of the surroundings, which varies

throughout the day and night. A further object of insulating a constant-temperature room is the elimination of a major portion of the wasted energy which otherwise would occur.

The function of insulating material is to reduce the rate of heat flow through the structure. It is necessary to distinguish clearly between the function which insulating material performs and the object for which it is employed. The thermal transmission, or rate of heat flow, through any given structure is constant under the influence of a constant difference of temperature between the surfaces, but the effect on the temperature of a body subject to a constant rate of heat reception or rejection depends upon the heat capacity of that body. Consider the case of heat flow at the rate of 1 B.Th.U. per hour to a body consisting of 1 lb. of water. In one hour the temperature of the water is raised 1° F. Supposing the rate of heat flow remains constant but that the heat capacity of the body is increased by the addition of another pound of water, the temperature rise per hour will then be halved. It is an indirect control over temperature which is exercised by insulating material. Constancy of temperature of the heating or cooling element is sought as a measure of running economy, and therefore variation of the heat duty required by reason of vacillating conditions is often taken care of by varying the length of time during which the heat plant is operated. The capacity of the heat plant should be adequate for the maximum duty required to be accomplished without continuous running. In refrigeration practice it is usual to allow for a normal running time not exceeding 16 hours per diem, which provides a margin of safety to permit adjustment and repair.

The running time of the heat plant is not usually a single period but is divided into two or more periods, particularly if the limits of temperature control are narrow. During the periods of intermission, the resistance to heat flow

offered by the insulation is the sole means of controlling variation of the temperature. The length of time during which intermission may be allowed to persist depends upon the heat capacity of the contents of the room and the rise or fall of temperature permissible. The degree of insulation is determined such that the resulting rate of heat flow permits reasonable intermission in the operation of the heat plant. In industrial application, a relatively long period of intermission is usually required where the plant is hand-operated, in order to avoid the necessity of attendance during the night. Thermostatic control of the plant provides greater elasticity in this respect.

Margin of Safety.—This will depend upon the importance attaching to constancy of temperature in the particular case and upon the seriousness of the consequences of possible breakdown of the heat plant. It may not be a matter of importance if the temperature of a hot room used for simple drying purposes varies widely (say within 25° F.). A process of this sort which has been interrupted may usually be resumed with impunity. On the other hand, any rise in temperature of a cold-room used for the preservation of organic matter, such as foodstuffs, involves increase of bacterial activity and may result in serious loss. Provision for such a contingency, coupled with the necessity for close limits of temperature control, has led to the adoption of lower rates of heat flow from the insulation of refrigerated rooms than in the case of the majority of higher temperature applications. A loss of 60 B.Th.U. per sq. ft. per hour would not be considered excessive for many steam plants, whereas it is usual in cold-store practice for the "loss" (actually gain) to lie in the region of 2·25 B.Th.U., except where the intermittent effect of solar radiation may result in an increased figure.

The insulation of steam plant is regarded mainly from the viewpoint of fuel economy, whereas in constant-tem-

perature rooms the maintenance of the required temperature is usually of greater importance than the value of the heat units saved. Any decrease in the efficiency of insulation of constant-temperature rooms may necessitate increase in the capacity of the heat plant required, or at the least an increase in the number of running hours. The more costly the insulation is in relation to the cost of heat extraction or addition, the greater will be the inclination to reduce the thickness in order to strike a balance of cost. The increase of heat flow involved in such a method may easily result in jeopardizing the success of the process concerned. The relation of cost with efficiency is discussed in Chapter III.

Origin of Applied Insulation.—Consideration of Thermal Insulation would be incomplete without reference to that employed with the earliest heat plant known—the human body. The process of heat generation by means of the intake of oxygen, the combustion of the carbon of the body and the expiration of carbon dioxide, is well known. The heat generated by this means is necessary to make good the loss of heat from the surface of the body and to maintain a constancy of temperature rarely required or achieved by applied science. The temperature of the body generally is higher than that of the atmosphere, and continuous rejection of heat occurs. In climates where the temperature of the air runs high, nature provides an alternative duty to the making good of sensible heat by substituting latent heat of evaporation, ensuring continuance of operation of the heat plant and preventing lapse into fatal disuse. Over a large part of the world a difference of temperature exists such as to induce man to adopt various types of clothing to serve as insulation. The function of this insulation is to restrain the rate of heat loss within the comfortable limits of the generating capacity of the heat plant. If increase of the rate of heat rejection becomes so great that it exceeds the maximum possible rate of heat generation of which the

body is capable, the temperature falls and the consequences need no description. The importance of insulation in preventing such an occurrence is obvious.

The operation of a constant-temperature room may be compared with that of the human body, although it lacks the flexibility which manipulation of the amount of insulation affords. The output of the heating or cooling system may be adjustable in some instances: in probably the majority, control rests with the length of time during which the heat plant operates at constant output. The same variation of temperature-gradient exists, but in the case of the constant-temperature room the degree of insulation must be based on the maximum temperature-difference which is reasonably to be anticipated at the particular location.

General Considerations in the Planning of Constant-Temperature Rooms.—The efficiency of insulation * to be adopted in any particular case should be reviewed in the light of the actual plant available. Insulation "loss" represents a definite proportion of the capacity of the plant, which runs to waste in contending with nature's urge towards equalization of temperature. Competitive commercial influences may indicate as desirable the adoption of a machine the size of which is barely adequate for the total calculated load, rather than employ the "next larger" size on the manufacturer's list, which might be unnecessarily large by a wide margin. In such border-line cases it may be advisable to increase the efficiency of insulation as a measure of easement towards the plant. Whereas the plant may be running for only a fraction of the time available, in many cases—and in that of cold stores in particular—the insulating material is fulfilling its function continuously throughout the day and night and often right through the year. The

* The expression "efficiency of insulation" conveys the ratio of the quantity of the heat flow which is frustrated to that which otherwise would occur but for the use of insulating material.

advantage of increased efficiency may therefore be utilized to the full, including, in addition, extension of the periods of intermission.

The rate of heat flow through any given slab of material varies inversely as its thickness, and the decrease of heat flow as the thickness is increased becomes arithmetically less for each succeeding unit of thickness. The cost of the material, however, increases directly with the thickness, or nearly so, and from the viewpoint of cost there is an obvious limit to the thickness desirable. In the majority of refrigerated rooms the rate of heat flow through the structure is mainly of importance in its effect on the rate of temperature rise which must ensue whenever the plant is stopped. The rate of alteration of temperature difference of a constant-temperature room is greatest at the moment of stopping the plant and becomes progressively less as the temperature-difference, which is the cause of the heat flow, itself becomes less. Where narrow limits of temperature control are required (say 3° F.), it is the maximum rate of temperature alteration which concerns the designer, and if this proves in practice to be greater than that forecast from calculation, the intermission periods will need to be shortened, with possible inconvenience of working. This may result in unreliability of temperature control, which however may be prevented by incorporating thermostatic control of the plant. The continuous control of the plant which this provides is particularly applicable to rooms of small capacity, as will be seen later. A rate of insulation "loss" adopted on the assumption that the contents of the room provide a certain heat capacity per unit of temperature will appear to make an inadequate contribution to constancy of temperature on occasions when the room is nearly empty, and the heat capacity thereby greatly reduced. This is of importance because, in practice, variation of the heat capacity is unavoidable, although the same constancy of temperature is desired whatever the degree of loading.

Decrease of the insulation "loss" beyond that determined as being in accord with the particular temperature-difference is not often justifiable. Until automatic control of refrigerating plant became a practical measure, the heat capacity of small cold rooms was bolstered up as a rule by the introduction of brine storage tanks in which the evaporating coil system was submerged. The additional heat capacity of the brine made possible intermission periods of a length which ensured convenience of operation. With thermostatic control of the plant, the length of the intermission periods is generally reduced, owing to the closer limits of temperature attained, and the number of intermission periods per diem is increased. The total running time of the plant is materially the same, as the insulation "loss" is dependent only on the temperature-difference.

It will be appreciated that thermal insulation plays a simple and easily identifiable part in what may be a somewhat complicated whole. The purchaser of constant-temperature equipment looks naturally for the fulfilment of the object which constituted the purpose of his purchase. But in passing judgment on such equipment it is important not to confuse the peculiar functions exercised by the various elements of the plant, and to bear in mind that it is possible for the insulation to be fulfilling its particular function to the degree expected, even though under some conditions the equipment appears to fail. A simple example of misconception on this point may be cited in connection with the testing of an insulated room immediately on completion. A not unusual method consists in shutting the (airtight) door and running the machine until the designed temperature is secured. Time is allowed for steady conditions to be attained, the machine is stopped, and temperature is then logged against time with the aid of a recording or distance thermometer. This method of reading the temperature is necessary in order to avoid vitiation of the test which would occur if the door had to be used for

access to the room. The fairly rapid attainment of the desired temperature in an empty room passes unnoticed or is regarded as a matter for congratulation on the capability of the equipment, but the subsequent rapid recession of temperature-difference causes unexpected disappointment, and the insulation is held to be at fault. The true position is that although the insulation may be fully capable of frustrating the flow of heat to the degree expected, the rate of heat flow is not maintained owing to the very low heat capacity of the reservoir to or from which heat is flowing. Insulating material, and other materials employed in its erection, contribute to the heat capacity of the room but not to any great extent, since the specific heat and weight of these materials are not high.

Natural Coolness.—The case may be cited of a cellar which is observed to be sufficiently cool throughout most of the year but which it would appear desirable to insulate against rise of temperature occurring in the height of summer, without the use of mechanical plant. In such circumstances it must be borne in mind that heat flows from the body at the higher temperature to that at the lower, and that therefore the observed coolness of the cellar is due to reception of heat from the air by the walls and floor in contact with earth. Should insulating material be applied to these surfaces, practically the whole cooling effect previously observed will be nullified, and the temperature of the cellar will rise. On the other hand, heat will be received by the air from the underside of the floor above, particularly when the atmospheric temperature is high. Direct interchange of the cellar air with warmer air above may occur where there is more than one opening into the cellar and a draught results, in spite of resistance to air flow occasioned by the greater density of the cooler air below. Insulation of the ceiling and the provision of airtight doors, etc., is the most that can be done. The presence of a person in

the cellar is the equivalent of a warming element, and the heat emitted by an electric lamp is also likely to have considerable influence on the temperature, particularly in small cellars. Only the provision of cooling plant of some sort will guarantee real constancy of temperature.

A further consideration which must be kept in mind when surveying a cool cellar is the fact that the lower and fairly constant temperatures which are sometimes experienced are due in many instances to dampness caused by porosity of the building materials. Circulation of air over surfaces which are maintained in a moist condition creates a natural cooling system in which the latent heat of evaporation constitutes the means of heat absorption. Insulation of the surfaces from which the moisture is derived would defeat the natural coolness at the outset, as would also the provision of airtight doors by preventing through circulation of air. A current of air is necessary in order to carry away the water vapour and assist evaporation. Any means adopted to close up the cellar with the idea of "retaining" the temperature will have the reverse effect to that desired.

It is clear that thermal insulation and some controllable means of extracting or supplying heat are concomitant essentials in the operation of a room in which the temperature is required to remain virtually constant. No doubt it is possible to arrange a continuous supply of cooling medium in liquid form, and to incorporate automatic control of the weight of liquid circulated at constant temperature, which would enable a reasonably constant air temperature to be maintained without resort to insulation. But such a method would be wasteful and costly, and too precarious for industrial application where reliability and convenience are always requirements of importance.

Maintenance of Heat Quantity.—There are a few applications in which it is reasonable and of practical value to

employ thermal insulation without any form of heat plant. In nearly all such cases it will be found that machinery is made use of at some period of the particular process, and that it is only in the closing stages of the process that sole control is relegated to the insulation. The main field of application lies in the transport of certain types of goods where it is desired to retain, as far as possible, the initial physical condition of the goods which has been created by artificial temperature production. Heavy oils which, by reason of their viscosity, are not amenable either to pumping or reasonable gravity flow, are heated before loading into insulated tanks. Some reduction of temperature will necessarily ensue owing to loss of heat on the journey, but the employment of insulating material makes possible the arrival at destination in a condition which is adequately fluid. As a precautionary measure or for long-distance transport, it is not unusual to incorporate an occasional heating system in the form of a pipe coil submerged in the fluid and arranged as a permanent fitting. If then for reasons of time or temperature the insulation is unable to fulfil entirely its purpose, steam is circulated through the coil by means of detachable pipe connections.

Tank wagons, both rail and road, are insulated for the conveyance of milk at temperatures below that of the atmosphere. Vans, similarly, are employed for the transport of meat, fish and other produce. In each case the temperature of the produce is brought to a reasonable level before loading. Flow of heat to waste occurs while loading and unloading, and during all the time occupied by transport, but it is so reduced by the presence of the insulating material that the resulting rise of temperature is not sufficient to jeopardize the condition of the produce when it arrives at its destination. Owing to the reduction in earning capacity which would result, it is not usually possible to afford the space which would be occupied by the thicknesses of insulation deemed necessary for the same temperature-differences in buildings,

but this disadvantage is offset by the increased heat capacity per cubic foot obtained by packing to repletion. Where the period of transport is extended, it is necessary to resort to some artificial means of cooling. This is effected by the provision inside the van of a tank containing ice, a mixture of ice and salt, or brine pre-cooled at the point of despatch. For the larger types of van, small refrigerating compressors are sometimes used.

Freezing in Winter.—Another insulation problem in which time is the dominating factor arises in the prevention of freezing of water tanks and cisterns. Insulation of the tank reduces the rate of heat flow away from the water, but does not prevent it entirely. Under prolonged exposure to air temperatures below 32° F., the temperature of the water is lowered gradually until finally freezing does occur. The time at which freezing commences, however, is postponed by a period of time which may be some six or more times longer than that in which freezing would have commenced if the tank had remained uninsulated. This postponement is often sufficient to tide over periods of low atmospheric temperature in these latitudes. Nevertheless the possibility of failure will not be eliminated unless some external source of heat is provided to replace that lost to the atmosphere. This may take the form of a steam coil or an electric heater, but a simple method of restoring heat quantity is to run the water off and replace with fresh.

Insulation in the case of domestic hot-water cylinders provides yet another example of its use in postponing loss of temperature-difference by reduction of the rate of heat flow. The interest of the householder lies not so much in the saving of fuel as in the maintenance of the temperature of the water over a longer period of time without the inconvenience of maintaining the source of heat throughout the night. The well-known vacuum flask for carrying hot beverages finds similar justification.

Portable Insulated Containers.—The hawking of ice-cream and its distribution from factory to retailer have been facilitated greatly by the employment of thermal insulation. Prior to its use, it was found necessary to transport ice-cream surrounded with a freezing mixture, owing to the considerable temperature-difference and the prospect of a possible change of state. The resulting dual container was both bulky and messy and has been superseded by insulated box containers. The temperature difference involved is often as great as 80° F., being enhanced by the higher atmospheric temperatures of the season in which ice-cream is more readily saleable. Further, storage space in these containers is valuable, and the total weight of the container itself is a matter of importance because of handling and mobility. Insulating material of low density and thermal conductivity is particularly necessary in this application of insulation. The difficulty of the race against time, i.e. the placing of the article in the hands of the consumer before the temperature rise has become such that the quality of the article is impaired, is increased by the relatively large area of such containers which is receptive to heat, compared with the initially small and ever-dwindling heat capacity of the contents as, one by one, the packages are removed for sale.

Amelioration of these conditions has been effected by the introduction into the container of small metal tanks filled with an eutectic mixture. These small tanks—known as "inserts"—are cooled down in a special tank or room to the cryohydric point of the particular solution employed, and are placed in the containers at the time they are loaded with ice-cream.

It has already been shown that if the quantity of heat flowing through the insulation per unit of time, however small a quantity it may be, is relatively large in comparison with the heat capacity per unit of temperature, the temperature-difference will alter rapidly. Conditions then are

likely to recur in small containers of this type under which the insulation, however efficient it may be of itself, is unable to achieve alone the object of maintaining the temperature necessary to successful operation. The capacity for absorbing heat possessed by the contents of the container is increased artificially by that required by the eutectic in changing from the crystalline to the fluid state. With a suitable choice of eutectic, a temperature at which this heat is taken up is obtained which conforms with the storage temperature desired.

With small packages the problem of thermal insulation becomes still more acute. The heat capacity per unit of temperature is very small in comparison with the surface exposed to reception of heat, and considerations of cost and space preclude the employment of a degree of insulation suitable to the temperature-difference. The moment that the package leaves the insulated container, the rate of heat flow is sufficient to cause rapid change of temperature. The insulating material may consist merely of corrugated paper and, in the case of ice-cream with the large temperature-difference to be maintained, the continued reception of heat at low temperature is often achieved by the insertion of a small quantity of solid carbon dioxide. The quantity of heat required by the carbon dioxide when undergoing sublimation increases the heat capacity of the package, and rise of temperature is deferred until sublimation is complete. The length of time during which rise of temperature is postponed depends upon the weight of carbon dioxide inserted in the package.

It is interesting to note, in connection with the use of solid carbon dioxide as a cooling agent, that, owing to the temperature at which sublimation occurs being so low (about $-108°$ F.), it is necessary in the majority of applications to raise artificially the temperature of the surface receiving heat. Otherwise overcooling would occur for most purposes of refrigeration. This is accomplished by shrouding with

insulating material the metal tank containing the CO_2. The effect is to raise the temperature of the surface receiving heat and to reduce the rate of heat flow to the CO_2, with resultant economy.

The foregoing examples of the application of insulation in directions which are not entirely concerned with structures have been inserted at some length in order to assist the newcomer to the subject to obtain a clear mental picture of the function which insulating materials perform. Insulation of boilers and steam or hot-water pipes is justified primarily by the saving of a considerable quantity of heat which has involved both trouble and expense in its generation. The same, of course, applies to constant-temperature rooms, but in nearly all cases there is the added importance of the fulfilment of some process. The importance of the goods undergoing process, or of consistency of manufactured product, far outweighs that of the heat units involved, while redemption of initial cost becomes a matter secondary to permanence of structure and consistency of behaviour. Economy of operation, instead of forming the basis on which insulation detail is determined, warrants only minor adjustment within the reasonable limits entailed by achievement of the purpose for which the constant-temperature room is designed.

CHAPTER II

INSULATING MATERIALS

Many different materials are employed to interpose resistance to the flow of heat from one body to another, occasioned by a difference of temperature of the bodies. The thermal conductivity of dense materials, such as metals, is high; that of solids of lower density, such as wood, is lower; and that of gases is lower still. A vacuum precludes the transfer of heat by conduction and convection, but except in the case of small flasks a vacuum is quite impracticable. If, therefore, conduction were the only means of heat transfer, a cushion of air between the two bodies at different temperatures would provide the most reasonable means of securing the highest efficiency of insulation. When air is heated it becomes less dense and tends to rise, allowing cooler air, which is more dense, to fall and take its place. By this means, circulation of air is set up between two bodies at different temperatures, and the convection currents so formed cause the air to act as a vehicle in the transfer of heat from the body at the higher temperature to that at the lower. If the difference of temperature is considerable and there is freedom from frictional resistance to air flow, the circulation of the air will be rapid and the rate of the transfer of heat will be high. If, however, either the temperature difference is small, or there is considerable resistance to air flow, the rate of transfer will be small. Confining the cushion of air in a sealed enclosure is the first step towards impeding the air currents. A further step forward is made by dividing the enclosure into a number of smaller enclosures, so that the overall temperature-difference becomes the summation of a number of lesser temperature differences. The rate of

circulation in these smaller enclosures is considerably reduced from that obtaining in a single large enclosure, owing to the reduction of the temperature-difference which causes movement of the air. Subdividing these smaller enclosures still further reduces the originating cause of the air currents and increases the frictional resistance to movement until finally, when the subdivisions are so small that the "cushion" can be described as being of a cellular formation, the confined air becomes virtually still. By such means will the transfer of heat by convection be reduced to a minimum. The skin of material forming the boundaries of the air cells must be very thin and itself of low thermal conductivity in order to make its proper contribution to the "cushion" as a whole.

But a third means exists by which heat is transferred—i.e. by radiation—the means by which the earth receives heat from the sun. The amount of heat transmitted by radiation from a body at higher temperature to a body at a lower temperature varies as the difference of the fourth power of the Absolute temperatures concerned. This same subdivision of the air cushion reduces the heat flow due to radiation to a minimum, since the closer together are the two temperatures T_1 and T_2 the less will be the amount $(T_1^4 - T_2^4)$ at a given mean temperature. It will be appreciated that the rate of heat flow across each cell must represent the rate of heat flow through the whole cushion, since there cannot be any speeding up or slowing down of flow in its passage, i.e. accumulation of heat, under the impulse of a constant temperature-difference. The thermal transmission through the subdivided air cushion will never become as low as the thermal conductivity of air (about 0·163), owing to the unavoidable presence of solid material necessary to form the subdivisions. Further, the closeness of approach depends upon the degree of subdivision and the nature of the boundary material. The consequence which emerges from this is that the thermal conductivity

of cellular materials varies both with the density of the particular material and with the position on the temperature scale, as series of tests have shown.

Air Spaces.—Tests on single air spaces in which the materials bounding the air space possessed an emissivity of from 0·9 to 0·95 show clearly the variation of thermal transmission across the air space with the mean temperature. A figure of 1·112 B.Th.U. at 40° F. mean temperature is found by Rowley and Algren for a width of air space of one inch.* This contrasts with a figure of about 0·26 B.Th.U for one-inch thickness of cork slab at this temperature.

The thermal transmission across air spaces increases considerably with decrease of width of air space for small fractions of an inch, but from $\frac{3}{4}$ in. upwards the variation is not great. The variation with temperature is such that at 150° F. mean temperature, the thermal transmission is approximately 50 per cent. greater than that at 20° F. Reference to Fig. 1 will show that the corresponding increase in the thermal conductivity of cork slab over the same temperature range is about 33 per cent. only, indicating the additional control over variation of the thermal conductivity afforded by the cellular nature of the material.

Cavity walls have become an accepted device in the construction of buildings, but it will be clear that the insulating effect which they afford is not of the same order as that available with insulating materials. In the early days of cold stores, a degree of insulation was obtained by building up several layers of tongued-and-grooved boards separated by small timber battens, thus forming an air space about one inch in thickness between each layer of boards. The individual thermal resistance offered by each of these surfaces provided in the aggregate an efficiency of insulation which was of practical value. A comparison may

* "Thermal Resistance of Air Spaces," by F. B. Rowley and A. B. Algren (*A.S.H.V.E. Trans.*, 35 (1929), 165).

be made with the several layers of clothing worn by human beings in general. Such an arrangement of timber was both costly and clumsy, for the overall thickness necessary to obtain reasonable efficiency was considerable. The modern counterpart of this device is made up of just as many layers of material, but each layer is only a few thousandths of an inch in thickness and consists of paper or thin metal sheet. A refinement has been added by corrugating each alternate layer and so reducing the ambit of air under thermo-siphon influence. The resistance to heat flow available from such materials is not so high as that from truly cellular materials, but nevertheless an equivalent efficiency of insulation results from a thickness of only a few inches of the newer materials as from the enormous bulk of their prototype.

It will be apparent that a possible improvement to this idea lies in providing the sides of these cavities with a lining of polished material having a low emissivity, and by this means reducing the effect of radiation. This has been done by utilizing aluminium foil, the polished surface of which has an emissivity of only 0·05 as against the 0·9–0·95 of most ordinary building materials. A number of layers of foil are employed and are separated by means of timber laths at the positions where the foil is secured to the housing which retains it. In order to defeat convection currents as far as possible, the foil is crumpled so as to make the surfaces irregular.

It should be noted that if a polished surface becomes oxidized, the emissivity figure is greatly increased and may rise to the average figure for building materials. Very thin sheet steel has also been used to form the laminations of this type of insulation, and is coated with lead as a necessary precaution against oxidation of the surfaces. It is essential to provide a retaining construction which is practically air-tight, not merely in order to prevent infiltration of air, but also to prevent the ingress of moisture, for which air acts

as a vehicle. Water is a comparatively good conductor of heat, and its presence increases the equivalent thermal conductivity of the material, apart from whatever damage it may cause. For the insulation of refrigerated rooms this type of material involves considerable difficulty in attempted prevention of condensation. The low weight however is an asset in the construction of insulated vehicles, where the tare needs to be kept as small a fraction as possible of the gross weight.

Tests have been carried out [7] * at the National Physical Laboratory in association with the Building Research Station to determine the thermal transmission through a structure consisting of a series of air spaces. A panel 32 in. × 32 in. was constructed of asbestos paper coated with aluminium foil. Four partitions divided the space between the hot and cold surfaces which were 5 in. apart, the partitions being separated by 1-in. air spaces. The aluminium-covered paper was glued on wooden frames of 1-in. section, with a similar strut down the centre of each frame to support the paper. Measurements were made with the surfaces orientated as specified in the Table below.

TABLE I [7]

Mean Temp. 77° F.	Equivalent Thermal Conductivity B.Th.U. per sq. ft. per inch. per 1° F. per hour	
	Hot Surface Uppermost	Cold Surface Uppermost
Surfaces Horizontal . .	0·49	0·55
,, 45° to Vertical.	0·55	0·64
,, Vertical . .	0·67	

The above figures have been corrected to allow for the

* Reference numbers in text are to entries in the Bibliography.

heat conducted through the wooden framework, and the 1-in. thickness of air space permits direct comparison with the thermal conductivities of homogeneous materials, in which unit of thickness they are expressed. The considerable effect of convection currents as the freedom of circulation is increased by change of orientation is evident from the figures.

Loose-packed Materials.—The natural insulation which animals indigenous to cold climates possess in the form of long fur has been copied in different ways. Animal hair itself has been used; asbestos fibre, straw, eel grass, and fibres shredded from canes and the bark of trees have also been utilized. Slag wool (silicate cotton) and glass fibres are other forms of the same type but artificially manufactured. These materials are themselves of low conductivity as a whole, but even those of higher conductivity, such as slag and glass, are effective owing to the very low density to which they are brought in the process of manufacture. The separation of the material into fibres provides the subdivision of the air space, the desirability of which has already been noted. The natural twist of such fibres and their irregular orientation with respect to each other provides in effect a multitude of air cells, although in general not sufficiently sealed as to prevent entirely the circulation of air under thermo-siphon influence. In order to minimize this effect, it is very necessary with this type of material to pursue a suitable density of packing. The optimum density for each material varies, and experiment is necessary for its determination. It may also vary according to whether the surface to be insulated is vertical or horizontal (see page 39).

Slag wool is made by blowing steam into molten blast-furnace slag, the resulting " needles " of fibres being hollow and their volume about eleven times that of the slag from which they are blown.

Glass fibre is made by drawing threads from molten glass. The hollow structure of straw appeals at once as having the basic requirement of an insulating material, but the diameter of the cylinders is large as compared with some cellular materials.

All these materials, consisting as they do of fine fibres, possess capillary attraction for moisture, as their nature suggests; and in permitting some degree of air movement within the space they occupy, they are more prone than solid materials to the accompanying increase of equivalent thermal conductivity and, in the case of low-temperature rooms, to freezing up solid in course of time owing to the cumulative effect of precipitation of moisture. This effect does not depend upon any natural absorbency inherent in the material itself, and it is very necessary to provide an airtight retaining construction at all temperatures below normal.

The formation of air spaces between the fibres of such materials indicates at once that over-compression may occur, either through the ramming in position being too vigorous or through the material being required to carry too high a column of its own weight. This may produce fracture or powdering of the material, as with slag wool and glass fibres, thus raising the conductivity at the points affected and causing air spaces to occur at the top of vertical surfaces as a result of settlement. Loose material packed about 14 lbs. per cu. ft. in an unbroken wall 15 ft. high will impose a very considerable load on that at the bottom of the wall in relation to its capacity for carrying load, and walls are often subdivided horizontally with this in view. Vibration transmitted from road or railway, or caused by trucks and the handling of heavy cases, also assists in causing settlement and consolidation. The increase of conductivity through such causes may be as much as from 10 to 40 per cent. Fibrous materials of animal and vegetable origin are suitable for temperatures up to that of boiling water, most of them

having an ignition temperature some 150° F. higher. Those of mineral origin, such as slag wool, asbestos and glass wool, may be used for higher temperatures and are in general use for the insulation of steam plant.

Fibrous Sheets and Mats.—The inconsistency in the percentage of voids in this type of material indicated above has led to the introduction of manufacturing processes by which fibrous materials are pressed or rolled into sheet or slab form. The advantages of this form are considerable. Structural strength is obtained and in some cases the necessity for separate retaining construction is obviated. The circulation of air in the interspaces is practically eliminated and the material can be cut and fitted into position. As a whole, the standard of thermal conductivity is maintained and, coupled with the other advantages mentioned, a definite improvement results. Absorption of moisture has not been overcome entirely.

Slag wool fibres are felted into mats with the aid of organic material, resulting in a density of about 15 lbs. per cu. ft. Wood fibres obtained by pulping spruce logs are treated with chemicals and rolled out into boards about $\frac{1}{2}$ in. thick, giving the finished sheet a density of $16\frac{1}{2}$ to $19\frac{1}{2}$ lbs. per cu. ft. This compares with the original density of the timber, from which they are made, of about 32 lbs. per cu. ft. Similar sheets made of shredded cane fibre have a density of $13\frac{1}{2}$ lbs. per cu. ft. Asbestos fibre and glass fibre similarly are felted into mats.

Kapok fibre is a silky fibre from the seed pod of the Ceiba tree. These fibres are hollow and somewhat similar to those of slag wool. When being felted they are combed into alignment, so that they lie in a direction normal to the direction of heat flow and thus take advantage of the small cross-section of the fibres. When made up in the form of soft slabs or panels, it is usual for the containing envelope to be of waterproof material such as bitumized paper or

cloth. Kapok is applied as a filling to cavities in a retaining construction of some sort.

Table II gives the thermal conductivity of typical materials :—

TABLE II [2]

	Density (lbs. per cu. ft.)	Mean Temp. ° F.	Conductivity (B.Th.U. per per sq. ft. per hour per in. thickness per 1° F. temp. diff.)
Slag Wool Slabs	15·0	30	0·305
	15·0	81	0·328
Kapok	0·5	50	0·26
	1·0	50	0·23
Insulating Board, Wood Fibre	16·5	75	0·34
	19·5	91	0·38
Insulating Board, Cane Fibre	13·5	74	0·427
Asbestos mats		100	0·36
Glass-fibre mats		44	0·276
		140	0·287

Insulating boards are made in sizes up to 14 ft. × 4 ft., and as they are self-supporting they can be used to form partitions of themselves with the aid of timber framework, as well as to form a lining for securing to an already existing construction.

Granular Materials.—Granular materials have been used widely for insulation purposes, the resistance to heat flow being provided by the large number of small air spaces between the granules, in addition to those which may be contained within the granules themselves. The material itself must be of low conductivity. Sawdust and cinders are not now considered seriously as insulating material, the former giving off heat when damp, and being liable to spontaneous combustion. Wood charcoal was in extensive use in the early days of cold stores, the cellular nature of the

material itself after ignition contributing largely to its value as an insulating material, in addition to the interspaces between the granules. It is very necessary to keep charcoal dry as it absorbs moisture readily and thereby loses much of its efficiency. The increase in conductivity of charcoal[2] initially dry, when used for temperatures below the wet-bulb temperature of the atmosphere, is in the region of 10 per cent. The density of charcoal is about 12 lbs. per cu. ft., or approximately one-third of the weight of the timber before ignition. It is somewhat liable to spontaneous ignition, more particularly when subjected to air currents. Retaining constructions may act as a flue if not made properly airtight, the circulation of air being assisted by the temperature-difference, and under such conditions the element of danger from this cause is a present possibility.

Cork in granulated form is another material of this type which requires a retaining construction, usually of timber, although it has been used to fill cavities in brick and concrete walls. Cork is the bark of a tree—the cork oak, which grows only in hot arid climates, mainly in North Africa and in Spain—and is Nature's means of enabling the tree to survive the desiccating effect to which it is subjected from continuous exposure to a pitiless sun. Cork contains a multitude of very small air-cells, and it is from this minute subdivision of the material that it derives its resistance to the flow of heat. The bark is stripped and broken up into granules, all of which should pass through a sieve of ½-in. mesh. The density depends upon the quality of the cork and may vary from 5 to 7½ lbs. per cu. ft. Woody and other foreign matter should not be present. Like other granular materials, cork is subject to capillary attraction of moisture and to circulation of air in the interspaces. The latter is less evident with fine granules than with coarse.

Regranulated cork, a by-product from the manufacture of cork slabs, is a slightly more efficient material than

granulated cork in the raw state. The density of packing is about 6·5 lbs. per cu. ft., the granules being small and packing well together.

Cork Slab with Foreign Binder.—Adhesives have been used to bind together granular material into slab form. The earliest endeavour in this direction consisted of mixing granulated cork with the minimum quantity of molten bitumen necessary and running the mixture into rectangular moulds. After the bitumen had cooled and set, the block of cork was removed from the mould and sawn up into slabs of suitable thickness. The conductivity figure, **k**, is in the region of 0·4 B.Th.U., being considerably increased by the comparatively high conductivity of the bitumen. This type of slab, known as the "agglomerated" slab, is cheap and useful where dampness has to be provided against, but is not now in much favour owing to the greatly improved conductivity of pure cork slab. The density is about 19 lbs. per cu. ft.

Pure Cork Slab.—Pure cork slab is made from good quality cork granules graded to remove the finer particles, expanded by being subjected to steam, and then filled into steel moulds. In the moulds the cork is compressed, and while it is still under pressure the moulds are passed through an oven at a temperature of about 450°–500° F. This baking causes the natural gum in the cork to run and to cement the granules together. After cooling, the slabs are removed from the moulds and, when cold, machined to the size and thickness required.

The conductivity of pure cork slab depends on the quality of raw cork from which it is made, and upon the density. Within limits the conductivity increases with the density, but, as it is necessary to combine structural strength with efficiency of insulation, it has not been found reasonable in practice to reduce the density below a minimum of about

8 lbs. per cu. ft. Even at this figure care is necessary in handling the slabs, and 9–10 lbs. per cu. ft. is a more usual density.

Experimentally, slabs have been made down to 5 lbs. per cu. ft., but at this density cohesion is inadequate for ordinary handling, apart from lack of capacity to carry load when erected in position. It is essential that cork slab used for independent walls should possess sufficient structural strength, and when used on floors the compression load it

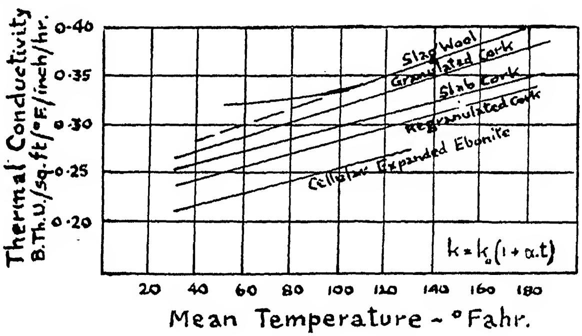


FIG. 1.

From conductivity figures published in *Heat Insulators* (Ref. 2, Bibliography)

is called upon to carry may be as high as 3 cwt. per sq. ft. Higher-density cork slab is made for the purpose of carrying greater loads, as for instance in machine foundations, in order to absorb vibration and sound, but in such cases the increased conductivity is not of importance.

Cork slab chars around 350° F. and is not generally used for temperatures above 212° F. The main field of utility is at temperatures below normal, and it is in general use for the insulation of cold stores down to − 20° F. It is also used for the insulation of chemical plants at still lower temperatures. It is not subject to capillary attraction of moisture, as are loose granular and fibrous materials, although somewhat absorbent when actually immersed in

water. In service it appears to retain its efficiency as an insulating material to a greater degree than most other materials. The thermal conductivity of typical slab and granulated cork is given in Fig. 1.

Cellular Expanded Ebonite.—The successful use of naturally cellular material, such as cork, has been followed by the manufacture of other materials in which the air-cells are formed by artificial methods. Cellular expanded ebonite has a lower thermal conductivity than the majority of insulating materials, coupled with a low density of about 5½ lbs. per cu. ft. The vulcanizing of the surfaces makes the slab less permeable to water, a defect associated with ordinary expanded rubber. The field of utility is mainly at temperatures below normal atmospheric. Owing to its light weight it is used largely for the insulation of portable containers, delivery tricycles and the like, where a double-skin construction lends itself to the housing of material of this type.

Lightweight Aggregates.—Another material of cellular type occurring naturally and which has been used for insulating purposes, is pumice. While it has not achieved any popularity in this country, in which there is no immediate source of supply, the increasing use of lightweight concretes has attached a new importance to this and other lightweight materials used as aggregates, such as coke breeze, foamed slag, expanded slate, and clay. The density of pumice is about 13·5 lbs. per cu. ft. and, as might be inferred from this comparatively high figure, the thermal conductivity [15] also is relatively high, being about 0·49 B.Th.U. per sq. ft. per inch thickness per 1° F. temperature-difference per hour.

Lightweight concretes have been used in various parts of Europe for panel fillings in framed buildings and for the inner leaf of cavity walls. They offer a considerably lower conductivity than other building materials of normal density

such as brick, concrete and stone, but the main object of their use so far has been economy of weight. Coupled with the advantage of low density is the disadvantage of considerable reduction in compressive strength, and difficulty due to water absorption. The latter produces a greater degree of expansion and shrinkage than occurs with ordinary concrete.

This class of material occupies an intermediate position between insulating material and building material, combining in a limited measure the appropriate qualities of each.

The Building Research Board have pursued investigation into the behaviour of these special aggregates and have published their results in a Bulletin.

The thermal conductivity[4] lies in the region of 1·1 to 2·8, varying according to the particular aggregate and mix. The compressive strength appears to be a somewhat inconsistent quantity and, with a few exceptions, to lie within the range 150–800 lbs. per sq. in.[4]

The low compressive strength available suggests that the most suitable application of these concretes rests in their substitution for ordinary concrete or brickwork in those portions of the structure where the compressive load is sufficiently low so as not to involve much, if any, increase of thickness on account of the substitution. The higher thermal conductivity as compared with most insulating materials prevents them being regarded as a serious competitor in the insulation of constant-temperature rooms in the industrial field, but the lower thermal conductivity as compared with ordinary concrete and brickwork suggests their suitability for use in buildings, such as dwelling-houses, where intensity of loading is of a relatively low order.

Timber.—Timber is not regarded as an insulator, although it is used widely in the construction of insulated buildings. The thermal conductivity varies according to the species and lies in the region of 0·7 to 1·2 B.Th.U. Timber therefore

shares with lightweight concretes an intermediate position between structural and insulating material, but its load-carrying capacity, coupled with relatively low density, accentuate its value as a structural material in buildings required for artificial temperature maintenance.

The conductivity range indicated above refers to the condition in which heat is flowing across the grain of the timber. This is the condition which nearly always obtains in structures such as, for instance, the boarding and framing of a partition wall or the joists and boarding of a floor. Where heat flows with the grain of timber, an increase of heat flow of about 80 per cent. occurs.

TABLE III.—THERMAL CONDUCTIVITY [15] OF TIMBERS USED AS STRUCTURAL MATERIAL

	k = (B.Th.U.)	Mean Temperature of Test
Spruce	0·76	68° F.
Deal	0·81	81° F.
Teak	0·81	81° F.
Pitch Pine	1·04	81° F.
Oak	1·11	81° F.

There are some unusually light timbers which have but little value as structural material but which possess a considerably lower conductivity than the average and consequently have been utilized as insulating material. These include Balsa wood, the density of which is only about 6 lbs. per cu. ft., and several others slightly heavier with conductivity in the region 0·33–0·50. Light timbers such as these are highly absorbent, and unless carefully protected from moisture, their relatively low conductivity when in the dry state would not be reproduced in practice.

The avidity with which Balsa wood absorbs water[2] is such that during immersion for a few days it is capable of absorbing twice its own weight of water.

The protection required must also possess the ability to resist impact, since these timbers are easily damaged. Indentation of light timbers occurs when unprotected, even with blunt instruments and light hand pressure.

CHAPTER III

BASIS OF CALCULATION

In the equations referred to in Chapter III, the following symbols have been adopted. They are included among those adopted in the British Standard *Definitions of Heat Insulating Terms and Methods of Determining Thermal Conductivity and Solar Reflectivity*, B.S.I., No. 874—1939.[1]

Q	Quantity of heat.	**T**	Absolute temperature.
$\mathbf{Q_r}$	Quantity of heat transferred by radiation.	**q**	Thermal transmission or rate of heat flow.
L	Thickness of slab with plane parallel faces, measured in the direction of heat flow.	**k**	Thermal conductivity.
		R	Thermal resistance.
		U	Thermal transmittance.
		S	Shape factor.
A	Area of hot or cold face.	**f**	Surface coefficient.
t	Temperature.	**E**	Emissivity.

Subscripts :				
	s	Surface.	1	Hot side.
	r	Radiation.	2	Cold side.

Thermal Conductivity.—The British Standard definition of Thermal Conductivity is set forth in the following words :— "It has been shown by experiment that in the steady state the quantity of heat passing per unit time through an area **A** forming part of a slab of uniform substance of indefinite extent is proportional to the area and to the temperature difference between the faces, and inversely proportional to the thickness of the slab, i.e.

$$\mathbf{q} = \mathbf{k.A.}\frac{(\mathbf{t_{s_1}} - \mathbf{t_{s_2}})}{\mathbf{L}}.$$

The thermal conductivity **k** is defined by this equation.

"Hence the thermal conductivity of a substance is measured by the quantity of heat which passes per unit time through unit area of a slab of indefinite extent and of unit thickness, when unit difference of temperature is established between its faces.

"Thermal conductivity is a characteristic property of the material and its value may vary with the density, porosity and temperature. In the case of a non-uniform material, the above equation defines a quantity which may be referred to as the 'equivalent thermal conductivity.'"

The units in which thermal conductivity is generally expressed are (*a*) on the C.G.S. system—gram-calories flowing per second through an area of one square centimetre of material of one centimetre thickness under a difference of temperature of one degree Centigrade between the faces, and (*b*) on the British system—B.Th.U. flowing per hour through an area of one square foot of material of one inch thickness under a difference of temperature of one degree Fahrenheit.

The British system appears to be more widely used by English-speaking peoples than the C.G.S. system, and therefore the graphs and tables which follow have been confined to these units. In addition, the symbols and notation adopted in the British Standard *Definitions of Heat Insulating Terms* have been adhered to throughout. The value of $\mathbf{k}$ expressed on the British system can be converted to the C.G.S. system simply by dividing by 2,903.

By definition, and considering unit area and unit temperature-difference, the variation of $\mathbf{q}$ with $\mathbf{L}$ per unit of time for any given material, is given by the equation

$$\mathbf{q} = \frac{\mathbf{k}}{\mathbf{L}}.$$

This equation is expressed graphically in Fig. 2, in which a value of $\mathbf{k}$ has been assumed of 0·3 B.Th.U. per sq. ft. per 1° F. temperature-difference per 1-in. thickness per hour.

It will be observed that doubling the thickness results in halving the heat flow, and that as the thickness is increased, the value of continuation of increase in thickness is diminished.

A very large number of experiments have been carried out by numerous investigators in many parts of the world, in order to determine the thermal conductivity of various materials. Unfortunately the methods employed in these experiments have varied so widely as to make much of

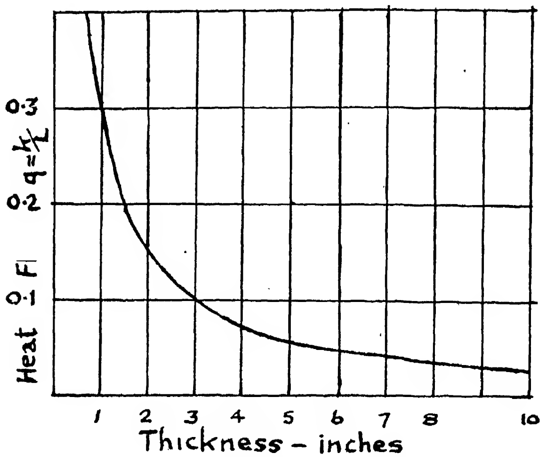


FIG. 2.—VARIATION OF HEAT FLOW INVERSELY WITH THICKNESS OF SLAB.

this work nugatory, and in many instances the records of the results do not include any indication of the degree of accuracy which, in the light of more recent knowledge, may be imputed to them.

Most early experiments were carried out by a box method. A sphere was used by some investigators, but more often a cubical or rectangular box having a double skin was employed. The width of the cavity was the same on all six sides, and within it was inserted the insulating material.

A known weight of ice was placed in the box, and by logging time with the loss of weight as the ice melted, the total gain of heat was calculated over a definite period. Materials of slab form which possessed sufficient strength, such as cork slab, were built up into box form, thus avoiding the necessity of a retaining construction. The latter involved a timber framework for which corrections required to be applied, owing to the different rate of heat flow through this portion of the box. The area needed to be calculated, and this produced a possible error of itself, as it has been demonstrated more recently that the equivalent area of a rectangular box is not the arithmetic mean of the internal and external areas in so far as the calculation of heat transmission is concerned. Error from this cause was enhanced through the thickness of insulation being large in comparison with the dimensions of the box. In some cases the thermal conductivity itself was not measured directly, but by recording the air temperature surrounding the box a figure for the thermal transmittance was obtained instead. Correction may or may not have been applied in order to determine the conductivity figure, but in any case such correction is of a somewhat arbitrary nature. Variations of this method included the provision of an insulated room in which the box was housed, and the employment of electrical methods of heating and of temperature recording.

The Determination of Thermal Conductivity.—Within recent years a reliable method of test has been evolved which avoids the errors and uncertainties in which earlier findings were shrouded and provides consistency of result. The method referred to is that used at the National Physical Laboratory at Teddington, Middlesex, and a brief description of the particular method used for materials of low thermal conductivity will be given. Modification of this method is made for materials of higher conductivity and for measurements at higher temperatures.

The following method [13] is used for measurement at hot face temperatures up to about 150° F. on materials of conductivity not greater than 0·9 B.Th.U. per sq. ft. per hour per 1° F. per in.

Two similar samples of the material to be tested are used, of a thickness between $1\frac{1}{2}$ and 2 in., if possible, and 12 in. square. The deviation from flatness should not exceed 0·005 in. for hard materials, though larger tolerances are permissible for compressible materials. The samples under test are placed one on each side of a hot plate, approximately 8 in. square, which is surrounded by a guard plate 12 in. square externally with a central square hole $\frac{1}{8}$ in. larger than the hot plate. Two cold plates, 12 in. square and cooled by brine or water flow, are placed on the outer sides of the samples, and they carry thermo-couples to measure the cold face temperature. Other thermo-couples are attached to the hot plate and the guard plate, each of which is provided with independent electrical windings. To carry out a test, the currents are adjusted so that the temperature of the guard plate is equal to that of the hot plate, when conditions have become steady. The energy dissipated in the hot plate is measured electrically, and the conductivity calculated from a knowledge of this quantity, regarded as flowing through a square of area half-way between that of the hot plate and that of the central hole in the guard plate, together with the observed hot and cold face temperatures.

A more detailed description of this method, together with a comprehensive description of results obtained on insulating materials, is given in a Special Report of the Department of Scientific and Industrial Research.[2] In obtaining these results, inconsistencies have been avoided by pursuing tests on each material at various temperatures and densities, and where apparent inconsequence of result has occurred, additional tests have been carried out in order to secure a reasonable explanation. Thus the effects of convection

currents in the interspaces of some insulating materials, and of a tendency towards increase of moisture content in others, have been determined.

Variation of Thermal Conductivity with Mean Temperature.—Series of tests on material in which the mean temperature was varied have shown that the thermal conductivity of cellular material depends upon the position of the mean temperature on the temperature scale. In Fig. 1 are shown some results of tests[2] on five materials, from which it will be seen that the conductivity approximates closely to a linear function of the temperature. It would not be unreasonable to anticipate a curvilinear form, in view of the variation of heat flow by radiation as the fourth powers of the Absolute Temperatures and by convection as the five-fourths power of the temperature-difference. Indeed, a curvilinear form is evident with materials in which the air cells are comparatively large, tested over a wide range of temperature. Over a moderate temperature range, located around the temperature of the atmosphere, the conductivity of these materials for all practical calculations may be accepted as conforming with the equation

$$\mathbf{k} = \mathbf{k}_0(1 + \alpha . t),$$

where $\mathbf{k}_0$ is the conductivity corresponding with a mean temperature of zero Fahrenheit. The appropriate value of $\mathbf{k}$ may thus be determined for use in calculations which, as applied to insulated structures, are concerned mainly with temperatures between 200° F. and − 25° F. Owing to the linear relationship, the conductivity corresponding with the mean of the hot face and cold face temperatures is the correct value on which to base the calculation, and this mean temperature will lie mainly above zero.

The curves shown in Fig. 1 are typically representative of high-grade material of the varieties stated. Values of $\mathbf{k}$ and $\boldsymbol{\alpha}$ derived from them are given in Table IV.

TABLE IV.[2]—THERMAL CONDUCTIVITY IN RELATION TO MEAN TEMPERATURE

Material	Density lbs. per cu. ft.	k_0 (B.Th.U.)	
Cork Slab	10·0	0·232	0·00277
Regranulated Cork (baked)	6·5	0·216	0·00311
Granulated Cork (raw) .	7·3	0·243	0·00311
Cellular Expanded Ebonite	5·4	0·186	0·00364
Slag Wool	15·0	0·253	0·00315

The interspaces occurring in loose-packed insulation constitute air-cells, albeit unsealed, and the value of smaller closed cells contained within the material itself is evident at all normally used temperatures. At very low temperatures, materials of the lower densities have the advantage, owing to the smaller proportion of solid matter, but the larger proportion of air space increases the risk of deterioration by moisture. The greater the proportion of void space, the greater is the rate of increase of conductivity as the mean temperature of the material is raised. Indication of this is provided by the value of α.

Variation of Conductivity through Convection Effects.—Tests carried out on loose-packed material[2] in apparatus capable of being rotated from the vertical to the horizontal have resulted in differing values of thermal conductivity being obtained for the two arrangements. The apparent explanation of this variation is that it is due to the activity of convection currents within the interspaces of the insulation when they are sufficiently large for comparative freedom of air movement to occur. In the horizontal position the ambit of circulation available is considerably more limited than in the vertical position, and the conductivity is found to be lower for the former than for the latter, except when the density of packing is so high that convection currents are practically eliminated. With coarse granular material,

it would seem impossible to eliminate them entirely, but with fine material such as regranulated cork, and with fibrous material such as slag wool, the percentage of voids can be reduced by careful packing to a suitable density.

TABLE V.[2]—CONVECTION EFFECTS WITHIN LOOSE-PACKED MATERIAL

Material	Density lbs. per cu. ft.	Mean Temp. ° F.	Horizontal Position k =	Vertical Position k =	Increase Per cent.
Charcoal . . .	11·5	28	0·369	0·386	4·6
Granulated Cork	5·4	37	0·328	0·345	5·2
	7·3	26	0·345	0·372	7·82
Eucalyptus Fibre	3·4	32	0·311	0·372	19·5

Further variation is evident according as to whether the hotter face is uppermost or lowermost—positions repre-

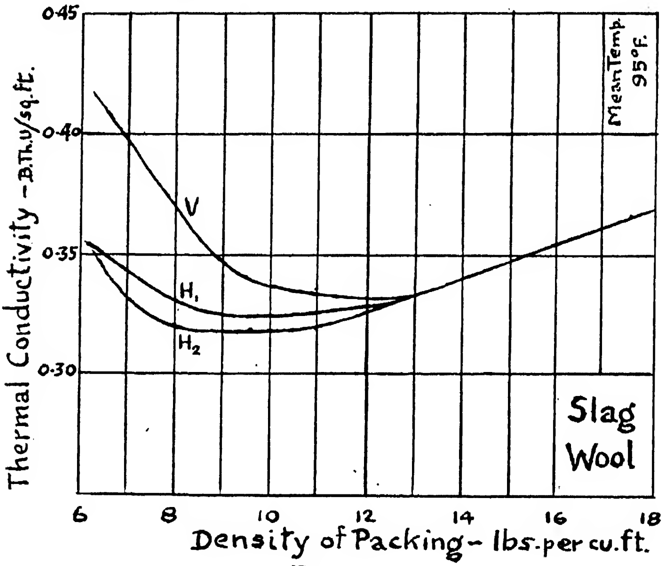


FIG. 3.

From figures published in *Heat Insulators* (British Units instead of C.G.S.)
(Ref. 2, Bibliography)

senting the ceiling and floor of a cold-room, and the floor and ceiling of a hot-room respectively. Fig. 3 shows graphically, results obtained with slag wool. From this the optimum density of packing in walls appears to be $12\frac{1}{2}$–13 lbs. per cu. ft. which may be reduced with advantage to 10 lbs. per cu. ft. in the floor of a cold-room and to 8–9 lbs. per cu. ft. for the ceiling. It must be remembered, however, that the conductivity of 0·325 which appears to be the mean for these conditions would only be obtained with slag wool which was in good condition and had not been broken down by pressure or vibration, or which had not become wet in service.

Variation of Conductivity with Density.—The variation of conductivity with the density of a particular insulating material is caused largely, but not entirely, by the percentage of voids in the material. In the case of slag wool the percentage of voids depends upon the degree of ramming, whereas with granulated cork (raw), poor quality of material is associated generally with largeness of granule and higher density. A figure of $5\frac{1}{2}$–6 lbs. for the latter represents good-quality material, and apart from the load imposed upon it by its own weight in vertical positions, but little variation of density can be effected in normal practice.

Cork slab can be manufactured in a wide range of density, the conductivity tending to increase with the density. For purposes of thermal insulation, the usual standard is 9–10 lbs. per cu. ft., although for other purposes the density may be three times as great. Reduced conductivity is possible at slightly lower density but at the expense of structural strength. The conductivity depends upon the quality and grading of the raw granulated cork used in the manufacture of the slabs and the correctness of the baking process in time and temperature. Conductivity tests show variation to an extent which makes it impossible to assume any mathematical relationship between conductivity and

density in all cases. The indication may be accepted that it is reasonable to anticipate a lower conductivity from a sample of solid material (e.g. cork slab) of low density than from one of a higher, but that it should not be taken for granted where the difference of density is small—say 1 lb.

Griffiths and Awbery,[3] in testing three different materials in connection with the insulation of solid carbon-dioxide containers, find that the conductivity at a mean temperature of $-13°$ F. approximates very closely to a linear function of the cube root of the density, i.e. of the linear spacing of the elementary particles of the material. The particular materials tested were:—Expanded rubber (5·4 lbs. per cu. ft.), Balsa wood (6·3 lbs.) and Cork slab (6·7 and 10 lbs.). They note that the temperature coefficient α in each case is considerably greater than that of air, indicating the specific influence of the solid material in these insulators in the temperature range examined.

Variation of Conductivity with Moisture Content.—Absorption of moisture increases the conductivity of insulating material. Tests on materials considered to be more than usually prone to absorb moisture have been extended over a longer period of time, in order to ascertain whether any increase in conductivity may be anticipated in service at low temperatures. Such materials include charcoal and slabs made of granulated cork, in which cohesion of the granules is secured through the agency of a foreign binder such as Portland cement. The initially dry material begins to take up moisture, the precipitation of which is assisted by the temperature, and the conductivity figure found at the commencement increases to a new level about 10 per cent. higher.[2]

Similar increase of conductivity occurs with materials which are not of themselves prone to moisture absorption but which are subject to capillary attraction of moisture, e.g. slag wool. The period of time in which a corresponding

degree of spoilage occurs may be gauged in weeks or months instead of in hours, depending upon the degree of airtightness achieved by the retaining construction and upon the porosity of the brick or concrete work, if such is present. Cellular rubber and cork slab are both capable of a considerable degree of water absorption when immersed, and timber used in construction is also liable to variation of moisture content. As the conductivity of water is approximately twelve times that considered to be the necessary qualification of an insulating material, the vital necessity of maintenance in a dry state will be appreciated. A considerable proportion of the thickness of the insulation used for a low-temperature room is itself at a low temperature, as will be seen from Fig. 10, and precipitation of moisture follows inevitably any access of warm, moisture-laden air to it. The resulting increase of conductivity facilitates further deposition, and the material finally becomes useless for insulation purposes.

Atmospheric Mean Temperature.—In the majority of calculations of thermal transmission in connection with constant-temperature rooms, it is necessary to assume a figure to represent the mean atmospheric temperature. This varies throughout the 24 hours of the day, and the highest and lowest daily temperatures vary with the seasons and in accordance with the position on the earth's surface at which they are read. The consulting of meteorological records compiled in the vicinity of the particular site under consideration is necessary to form a reasonable estimate of the temperature for which allowance should be made. Fig. 4 shows air-temperature records from Kew Observatory near London, the figures being abstracted from the *Observatories Year Book* for 1937. The centre curve shows the mean over the particular month of the mean temperature of each 24-hour day during the month. The upper and lower curves show the highest and lowest mean-temperature-over-24-hours which happened to occur on some particular day in each

month. The highest daily mean temperature (24 hours) occurred in June and is recorded hour by hour in the broken curve at the top of the chart. The warmest month as a whole was July. Similarly the lowest daily mean temperature (24 hours) occurred in December and is recorded hour by hour in the broken curve near the bottom of the

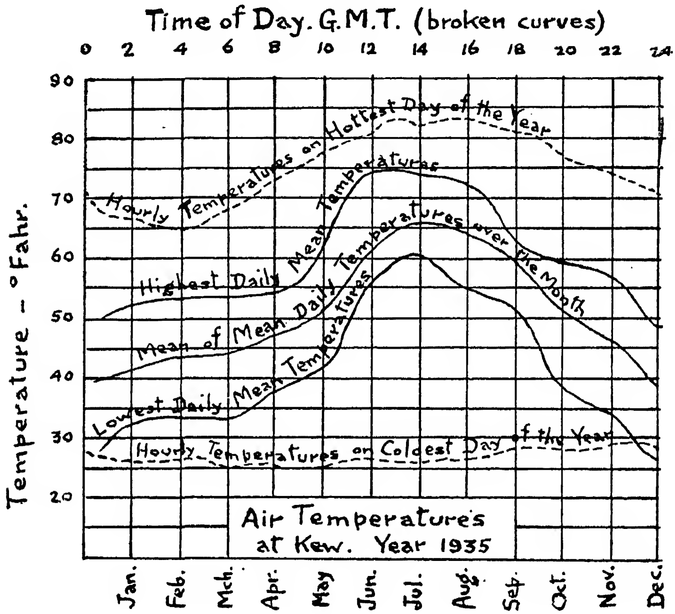


FIG. 4.

chart. This record is given here as a typical case and is fairly representative of the conditions to be allowed for in this country. In other latitudes the temperatures encountered may be higher and the range of temperature from highest to lowest throughout the year may be considerably wider. It is not possible therefore to adopt a mean figure of temperature which might be of any wide application.

Taking Fig. 4 as a basis of illustration, it will be seen that

the month of highest general temperature is July, and that of lowest temperature is December. The highest temperature is considered in connection with rooms at temperatures below normal and the lowest in connection with those at temperatures above normal. For rooms required to be maintained around normal factory temperatures, such as those used to house instruments and gauges measuring to fine limits, both figures must be taken into account in order to determine the maximum variation in each direction. The heat plant attached to a constant-temperature room is required to accomplish its duty under the worst conditions likely to be encountered, and therefore it is with a reasonable average of successive high (or low) temperatures that the designer is concerned. They will not be the actual maximum and minimum temperatures recorded, as these are of short duration and are reached probably only once in the year. In the particular year recorded in Fig. 4 the highest temperature registered was 84·5° F. and the lowest 25° F. On the other hand, the averaging of daily temperatures over a month does not indicate a possible period of one week during that month in which the day temperature may have regularly exceeded the average figure, and which might prove to be a period of difficulty to the heat plant.

The problem of estimating this figure may be viewed in two ways. In Chapter I it was seen that the normal duty of the heat plant should be accomplished in some fraction of the 24 hours per diem available. Considerations of convenience, attendance on the plant, or limitation of working periods for reasons of electric supply, may demand a definite maximum number of running hours, any excess over which would be regarded as creating an emergency. In this case it is safer to assume an atmospheric temperature some 10° F. higher than the apparent arithmetic average. The average of the mean-temperatures-over-24-hours recorded in Fig. 4 is 66·2° F. for July, while the mean-temperature-over-24-hours on the hottest day (June 24) was 74·7° F.

The latter occurred only once in the year and was higher than that recorded on any day in July, in which month occurred the actual highest air temperature of the year. The occurrence of temperatures over 75° F. for a period of 12 consecutive hours on a single day may induce some designers to adopt 80° F. as the expected maximum air temperature. Provided that proper allowance is made for solar radiation where necessary, others will consider the highest mean-over-24-hours of 74·7° F. to be a sufficient figure. The importance of solar radiation is such that it may double or treble the rate of heat flow calculated on difference of air temperature alone, and on no account should it be ignored.

An atmospheric temperature of 75° F. in this country is not likely to persist for any great length of time, and the designer who has postulated a maximum running time of 16 hours per diem based on this temperature is likely to find that it is only on rare occasions that the insulation "loss" reaches the designed maximum figure and therefore necessitates the maximum running time due to this cause. Under all other atmospheric temperatures his plant will be operating for only a proportion of the allotted maximum time.

In the alternative view, the total number of hours per annum during which the atmospheric temperature exceeds the mean daily temperature of the hottest months is small, and is regarded as a temporary overload. Rate of heat flow varies directly as the temperature-difference and therefore the duty allotted to insulation "loss" is increased in strict proportion. A 20-per-cent. increase of heat flow will not increase the running time by any more than the same amount, other things being equal, and as in most cases there will be a possible 50-per-cent. or more increase of time available for running, there remains a sufficient margin of safety. In this view, and in anticipation of occasional overload, the postulated maximum running time of the plant is

likely to be less than in the first case. But the smaller temperature-difference assumed in the second viewpoint may lead the designer to adopt a lesser thickness of insulating material than the greater temperature-difference of the first indicates, and this may prove to be a source of trouble when the atmospheric temperature is at its extreme. Further, an increase of 10° F. in the atmospheric temperature causes a greater proportionate increase of heat flow into rooms of moderate temperature—say 35° F. upwards—than in rooms of low temperature, and on the whole the safer method appears to require the adoption of a figure representative of the highest temperature likely to be sustained over a period of days. The record for the months of June and July given as examples in Fig. 4 suggests 75° F. as the reasonable figure.

It is during the hottest period of the year that the importance of temperature control in cold rooms is greatest, and this synchronizes with the period of operation most onerous to the plant. Hence the necessity of adopting a high figure to represent the atmospheric temperature. Throughout the remainder of the year, the duty is less than that calculated, and the plant then enjoys longer intermission periods and a wider margin of safety.

Similar considerations may be applied to rooms at temperatures higher than normal, but it will be noted from Fig. 4 that the range of temperature associated with the coldest day is very small. The lowest daily mean-temperature-over-24-hours is 26·8° F. (Dec. 23), whereas the mean of mean-daily-temperatures-over-the-month is 39·2° F. Most designers are likely to consider 30° as the appropriate figure for calculations, but the consistently low temperature on the coldest day should be noted.

There are numerous instances in which a space arranged for constant-temperature purposes is contained wholly within a building, the bounding surfaces of which are nowhere exposed directly to the atmosphere. As a rule, the

air temperature inside a building does not vary to the same extent as that of the atmosphere. It is more easily determinable, and the possible variation can be anticipated with greater accuracy. A hot room within a building may have the advantage of a fairly constant air temperature adjacent to it, owing to the presence of the usual heating plant with which the majority of buildings are provided. On the other hand, the proximity of a boiler-house or baking-ovens may necessitate increase of thickness of insulation of a cold store on some, if not on all, of the bounding surfaces.

Earth Temperature.—The temperature of the earth at a depth of 1 ft. does not vary over as wide a range as that

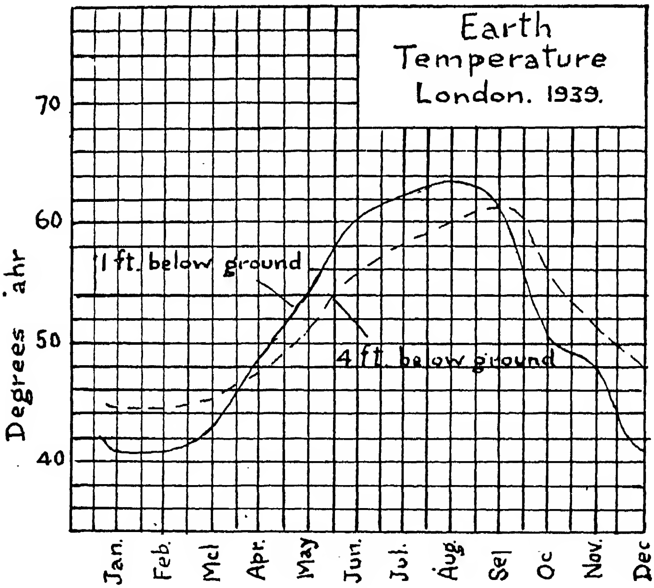


FIG. 5.

of the atmosphere, and at a depth of 4 ft. the extremes are still closer together, as indicated by Fig. 5. The reluctance

to change of temperature is reflected in the lag of the temperature at 4 ft. behind that at 1 ft. and the lower value of the maximum. Advantage may be taken of this greater constancy of outside temperature when deciding the thickness of insulation on floors and walls abutting on to earth, and economy of expenditure can thus be achieved.

The determination of the rate of heat flow through a floor laid upon earth is not the simple problem arising out of the distance between two parallel isothermal surfaces and the conductivity of the particular material which separates them. The floor surface itself may be accepted as an isothermal plane, but in order to obtain a figure to represent the rate of heat flow it is necessary to identify a second isothermal plane somewhere beneath.

The temperature of the earth near the surface has been examined by several observers and is found to be undergoing continual change. This is due to the residue of diurnal reception of heat by solar radiation and nocturnal rejection of heat by re-radiation. Thus, as the hours of daylight increase in number and the angle of incidence of the sun's rays approaches nearer to the normal to the earth's surface at any particular location, so the trend of temperature-movement of the earth is upwards. Correspondingly a recession of temperature occurs in the other half of the year. The considerable heat capacity of a large mass of soil causes a time-lag in the occurrence of the maximum and minimum temperatures behind those of the atmosphere. For example, at a depth of say 3 ft., the limit temperatures may occur some two months later than the warmest and coldest days of the year as determined from air temperatures. In addition, the range of temperature is considerably less than that of the atmosphere, and lessens progressively as the distance from the surface increases.

Series of tests taken by Forbes at Edinburgh (*Trans. Royal Soc. of Edinburgh*, **16**) provide an example. One series refers to sandstone, the temperatures being observed

at depths of 3, 6, 12 and 24 ft. and being averages over five years. Fair curves drawn through the figures recorded are shown graphically in Fig. 6, from which will be noted the reluctance to change of temperature of such a large mass resulting in a curvilinear form, instead of the single temperature-gradient which occurs through homogeneous material between two constant isothermal surfaces. The approach to constancy of temperature at a depth of about 30 ft. and at a temperature of about 46° F. at this location suggests the assumption of these conditions for the purposes of calculation in regard to heat flow through floors in contact with earth. A corollary assumption accepts this plane as being sufficiently far removed from the surface to be practically unaffected by the imposition of a building on the surface. Any variation which might be incurred due to a cold-store building would presumably cause only a reduction in the temperature at this depth.

The natural rate of heat flow in the uncovered ground to which the graph refers reaches a mean value of $\pm$ 0·4 B.Th.U. per sq. ft. per hour at 3 ft. at the time of highest and lowest temperatures at this depth. The effect of creating artificially an isothermal plane at the surface is to straighten out the curvilinear form of the temperature curve, and at the centre of a large floor area, and after the lapse of sufficient time (possibly several months) for the effect of the heat capacity to be overcome, the temperature gradient may become linear, or approximately so.

With small buildings, and close to the walls of larger buildings, flow of heat laterally in the ground will affect the temperature distribution.

On the basis of these assumptions it is evident that the creation (say) at 3 ft. depth of an isothermal plane at 38° F. (see Fig. 6) would result in the rate of heat flow tending in the course of time to fall to a limiting value of

$$k.(46-38)/27.12 = 2k/81 \text{ B.Th.U. per sq. ft. per hour,}$$

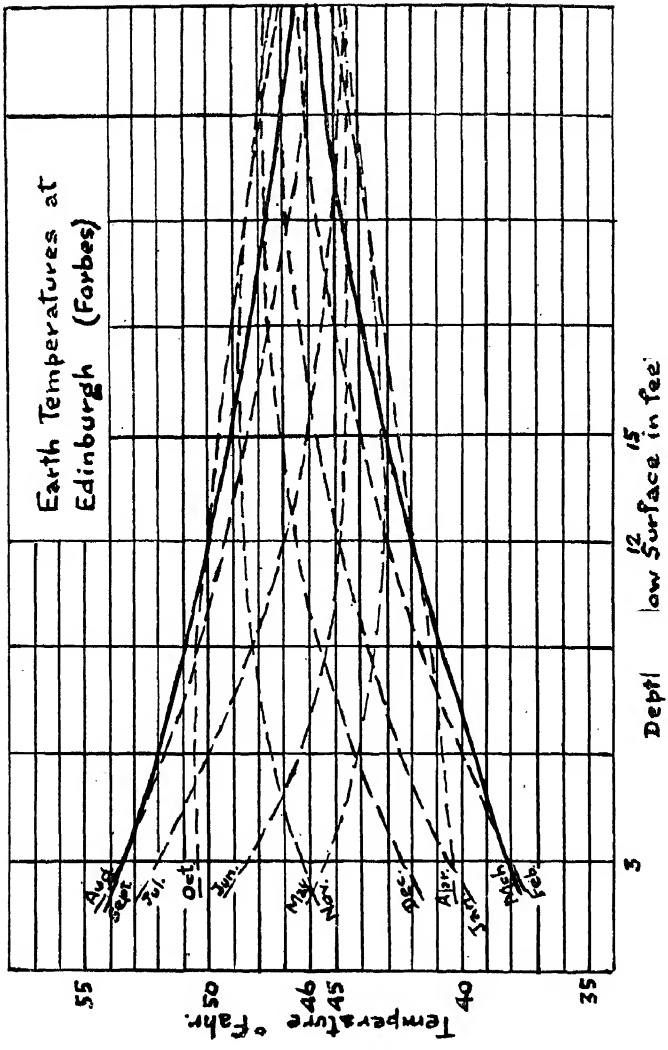

Earth Temperatures at Edinburgh (Forbes)
Depth below Surface in feet
3
12
15
Temperature °Fahr.
55
50
46
45
40
35
Aug.
Sept.
Jul.
Oct.
Jun.
May
Nov.
Dec.
Apr.
Jan.
Mch.
Feb.

FIG. 6.

subject to no interference in a lateral direction. The latter is true probably only at one period of the year, i.e. February–March, as shown in Fig. 6. Since the value of **k** will be in the region 7–10, it will be observed that the value of **q** is considerably lower than that expected for walls and roofs.

The application of insulating material on the floor, in effect, is equivalent to increasing the distance between the

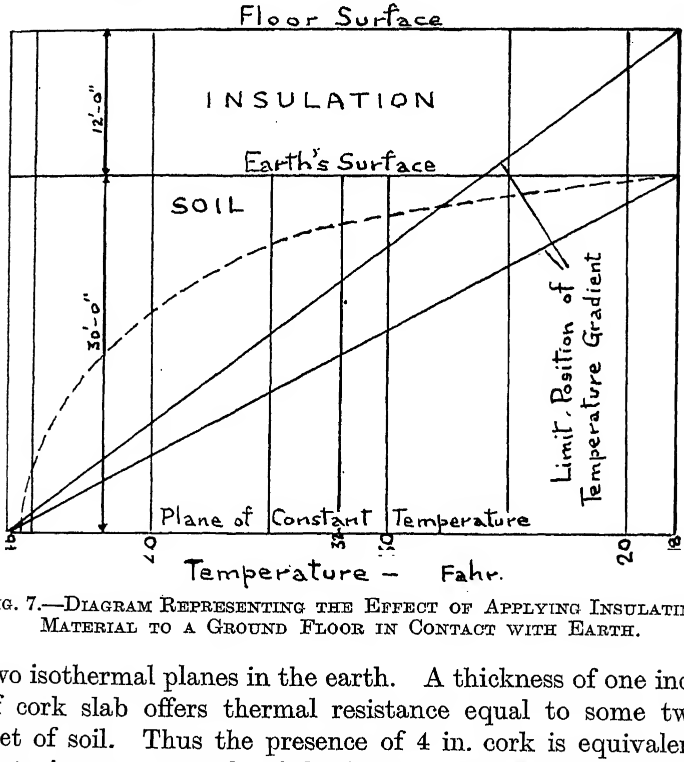


FIG. 7.—DIAGRAM REPRESENTING THE EFFECT OF APPLYING INSULATING MATERIAL TO A GROUND FLOOR IN CONTACT WITH EARTH.

two isothermal planes in the earth. A thickness of one inch of cork slab offers thermal resistance equal to some two feet of soil. Thus the presence of 4 in. cork is equivalent to an increase to 38 ft. of the distance presumed initially to be 30 ft. The corresponding figure for 6 in. cork is 42 ft. Evidently, the relative values of different thicknesses of insulating material in contact with earth are dissimilar from those provided by simple slabs in contact with air on

both faces, where the value of **q** varies inversely as the thickness.

The thicknesses of base concrete and floor topping are not considered separately, as the conductivity of concrete is very nearly the same as that of soil. This being so, a variation of a few inches is not of great importance where 30 ft. depth is being considered. But the actual quantity of heat flow through a cold-store floor may be a matter of quite secondary importance where the building temperature is below the freezing-point of water. In Fig. 7 are shown two isothermal planes distant 30 ft. apart in earth, the temperature of the one being 46° F., as already assumed, and that of the other, representing a cold-room floor, is taken as 18° F. In course of time the (broken) curve of temperature-distribution tends to flatten into the linear form shown. This transition carries the plane of 32° F. temperature a greater distance into the earth. Already a considerable depth of earth is at temperatures below the freezing-point of water, and in cases where the water table is only a matter of a few feet below surface level, it is possible for ice to be formed.

Ice Formation under Cold-Store Buildings.—The consequences of ice formation under a building will often prove to be serious. There is no indication of incipient trouble, and the evidence is not likely to be noticed until the condition is well advanced, because lifting of the floor is very small. The expansion in volume which occurs when water is frozen is small, and the visible increase of volume is only one-sixteenth the whole amount of ice present. Further, the ground below is mostly solid matter, and the water content is likely to be no more than some 15 per cent. of the whole. Therefore, at this percentage of moisture, the whole volume of moist earth which is frozen solid is over a hundred times greater than that of the small visible increase represented by the bulge in the floor. Thus a visible

bulging of the floor of one inch may involve a total depth of freezing of about 9 ft. The thermal conductivity of ice is twice that of soil, and this facilitates increase of the domain of freezing. When once originated, the formation of ice becomes more rapid. Nor is it necessary for a high water-level to be maintained continuously under the building. A heavy storm may cause a temporary high level in ground which is slow to drain, whether through the position of the building in relation to neighbouring ground or due to clay subsoil.

In the case of buildings used for other purposes, this tardiness of draining is of little or no importance, but in the case of a cold store some of the water may remain behind in the form of ice. When the water level falls in the natural course of things, the ice does not disappear, but persists in position. The next rise of water level adds its quota of ice, and each increase in the depth of ice carries the domain of freezing further down, to contribute still more effectively to extension of that domain.

Wall and stanchion foundations may become endangered, and so the safety of the structure itself. Masonry which has become saturated with water and then frozen splits easily. The enormous forces involved in the change of a confined liquid from the fluid to the solid state are not to be withstood by mere weight of brick or concrete work, and the building structure must yield to them. Outer walls receiving heat from the atmosphere, and possibly by direct radiation, are not usually affected until the trouble has been evident for a year or two, but internal walls, masonry piers, sleeper walls and the floor itself receive the brunt of the attack. Thawing out by process of time involves a length of period comparable with that taken for the trouble to manifest itself, and this means interruption of the activities of the storage concerned for an inconveniently long time. In addition, artificially applied heat is restrained in its effect by the considerable thickness of frozen material and

the availability only of the upper surface for its application. The removing of the affected volume of material by mechanical means is complicated by the almost certain extension below the level of the building foundations.

Wherever it is known that the water table of a particular site is high, or even if there is doubt on the matter and reliance cannot be placed on the proper drainage of the soil, the ground floor should not be laid in direct contact with the earth but should be formed as a suspended floor with a sufficient air space underneath.

This arrangement surrenders the advantage of the reduced heat flow through floors in contact with earth, but the circulation of atmospheric air under the floor enables the sub-floor to react to the seasonal change in a manner more nearly comparable with the floor of a building used for normal temperatures. It may be necessary to tank the sub-floor with asphalt, in order to prevent access of water and the effects of capillary attraction of semi-porous building material. In any case, the interspace should be well ventilated and restriction of air-flow avoided.

Greater importance must be imputed to the possibility of structural damage than to a small increase in the insulation loss. In one case which came to the author's notice a 6-in. thickness of cork slab failed to prevent ice-formation at a room temperature of 15° F., and when for an extended period the temperature was reduced to 5° F. the whole floor rose some 12 in., sloping steeply at the walls. In another case, owing to inavailability of other insulating material at the time of building, blast-furnace slag was employed for the floor. This was laid to a thickness of $2\frac{1}{4}$ ft. in order to obtain a rate of heat flow comparable with that of cork, and this increased thickness may have been sufficient to inaugurate the trouble. In this case the underside of the slag was made watertight with a screed of asphalt. In a third case, concrete foundations for carrying heavy coolers were found to have been carried on the base

concrete and therefore to penetrate the floor insulation. No doubt this was done with the object of relieving the cork insulation of the 6-ton load represented by a cooler, but that such an arrangement is not sound practice is exemplified by the results which followed. (See "Compressive Loading of Cork Slab," p. 133.)

Where refrigerated buildings are to be erected on low-lying ground near the sea or a river, close consideration of flood-water level is imperative. If the building temperature is higher than, but near to the freezing-point of water, the possibility of a local lower temperature at an air-cooler should be borne in mind.

Fig. 8 illustrates a possible disposition of isothermals in the ground at the time of the year of highest surface temperatures and presuming a condition of stability. The latter appears to be never entirely the case outside the area of the building, but the constant temperature of the floor surface will assist stability, particularly as the centre of the building is approached.

The equidistant isothermals shown indicate a temperature-gradient of linear form which, it will be observed, varies from a maximum immediately inside the walls to a minimum some distance interior to them. Under the particular conditions taken, the heat flow varies from 2 B.Th.U. per sq. ft. per hour at the walls to 1 B.Th.U. at 13½ ft. distance from them and to 0·39 B.Th.U. at 32 ft. away. The diagram is simplified by representing the floor-insulation as a thickness of soil of 12 ft., the conductance of which is equivalent to a 6-in. thickness of cork slab. It is assumed that all heat flow is upwards through the floor and therefore that the thickness of the floor-insulation does not present any additional surface to heat reception. It seems reasonable to suppose that the isothermal of 46° F., taken as datum level of temperature in this diagram, might not remain parallel with the floor surface of the building, but that in course of time it would dip to a minimum immediately

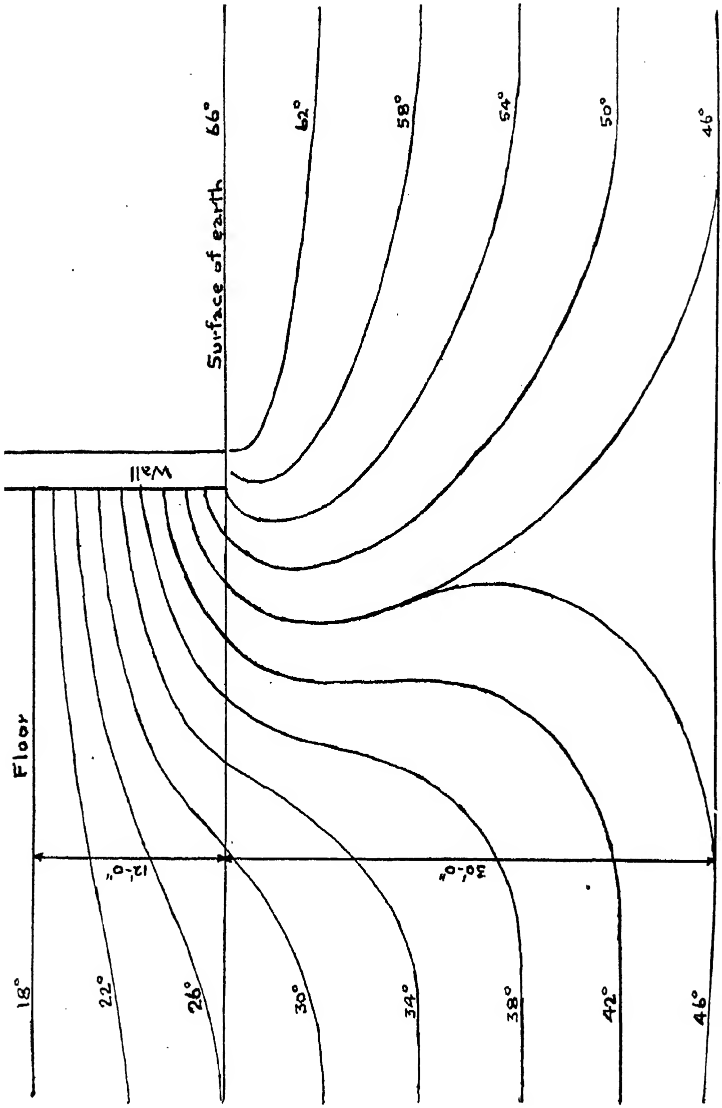


FIG. 8.—POSSIBLE DISPOSITION OF ISOTHERMALS IN SOIL BELOW A LARGE COLD-STORE IN SUMMER.

under the central point of the building. If this were to occur, it would involve a reduction in the already low rate of heat flow at this point. From the practical point of view, the higher rate of heat flow near to the walls determines the thickness of insulating material required. The positions of the lower rates of heat flow involve a considerable distance from the walls, and floor areas which are small in comparison with the depth of the datum level of temperature will incur only the higher values for a given thickness of insulation and building temperature. (See "Omission of Floor Insulation," p. 116.)

It will be observed that the area of floor subject to the highest rate of heat flow is greater than the areas subject to lower rates. This will be obvious if the floor area is divided up into a series of concentric rectangular annuli of equal width, since the area of the annulus adjacent to the walls is greater than that of its immediate neighbour, and so on.

The disposition of isothermals at the time of lowest temperature of the earth's surface under conditions of stability would be represented by a series of lines approximately parallel with the datum level of temperature. The temperature-gradient resulting from the building temperature and insulation thickness shown in the diagram would then be not more than 4° F. in 6 ft. over the whole floor area. This gives a heat flow of about 0·39 B.Th.U. per sq. ft. per hour, depending on the particular subsoil.

Before leaving this subject it is interesting to note the position of the 32° isothermal, which may reach a depth of some 9 ft. below the insulating material in spite of the high efficiency of the latter. This illustrates the necessity of adequately drained subsoil under large buildings maintained at temperatures below the freezing-point of water. The position of this particular isothermal would be higher when first the building is put into commission at low temperature, and would gradually descend to what may be

described as its limiting position as sensible heat continues to be extracted from the soil.

The example of temperature distribution in the earth as shown in Fig. 8 has been included here because the test figures are on record. The surface temperature of the earth varies with the latitude of the particular location, exemplified by the following figures taken from the Smithsonian Physical Tables :—

Variation of Surface Temperatures at	Lat. 40° N.—73·3° to 41° F.
	,, 50° N.—64·5° to 19° F.
	,, 60° N.—57·3° to 3° F.

The mean temperatures are respectively 58·1°, 41·7° and 30·1° F., but, for a given diffusivity, the depths at which the amplitude of a temperature-wave becomes the same in each case will vary, increasing with the angle of Latitude.

Those who are interested in the mathematics of this type of problem may refer to a discussion by Awbery in the July, 1937, issue of *Ice and Cold Storage*. The author shows that for a floor of given dimensions an effective area can be derived which takes into account the effect of the spreading of the flow lines, and so the total heat flow can be calculated for the particular floor. The mathematical solution put forward is that due originally to Sir J. J. Thomson * and involves resort to elliptic integrals.

Surface Coefficient.—The thermal resistance offered by an insulating structure is not that of the insulating material alone. Building materials such as brick, concrete and timber add to the thermal resistance, and this is supplemented by the resistance to heat flow offered by a surface in contact with a fluid. Normally there will be at least two surfaces involved, and usually the thermal resistance of each will not be the same.

Surface coefficient is defined [1] as " the thermal transmission per unit area due to convection and radiation,

* *Recent Researches in Electricity and Magnetism*, p. 246.

divided by the temperature-difference between the surface and the neighbouring air or other fluid." It is a fundamental requirement that difference of temperature must exist for flow of heat to occur. The quantity of heat received or yielded by a surface under the influence of unit temperature-difference between the surface and the fluid (whether a gas or a liquid) in contact with it, is the measure of the obstruction offered to heat flow. The quantity varies with the temperature and with the velocity and direction of flow of the fluid. The smoothness of the particular surface also affects the amount of flow.

The surface coefficient on surfaces exposed to the atmosphere is generally higher than that on the inside surfaces of a room, which is taken as that applying to still air. The exposure of outside surfaces to wind makes the surface coefficient a variable quantity according to weather conditions, and here it is necessary to adopt a mean value. A figure corresponding with a wind velocity not exceeding 10 m.p.h. is suggested as being suitable for use in calculation of duty. Higher velocities occur mainly when the temperature of the atmosphere and the intensity of solar radiation are not at their highest, and are also intermittent. Special allowance may be necessary for wind velocity in some parts of the world where conditions are more onerous.

Heat transfer between a surface and the ambient air occurs both by convection and radiation. Experiment [9] has shown that heat transfer due to convection varies as the five-fourths power of the temperature-difference between the air and the surface, and also varies with the orientation of the surface. That due to radiation varies as the difference of the fourth power of the absolute temperatures of the surface and its surroundings, and also depends upon the emissivity of the particular surface.

Thus

$$f = \frac{C(t_s - t_a)^{\frac{5}{4}} + 16.E.10^{-10}(T_s^4 - T_a^4)}{t_s - t_a},$$

which assumes that the temperature of the surroundings is the same as the air temperature. The value of **E** for most ordinary building materials is about 0·9, based on a value of unity for a perfectly black body.

The value of **C** has been determined by experiment [9] and may be taken as 0·30 for a vertical surface, 0·38 for a hori-

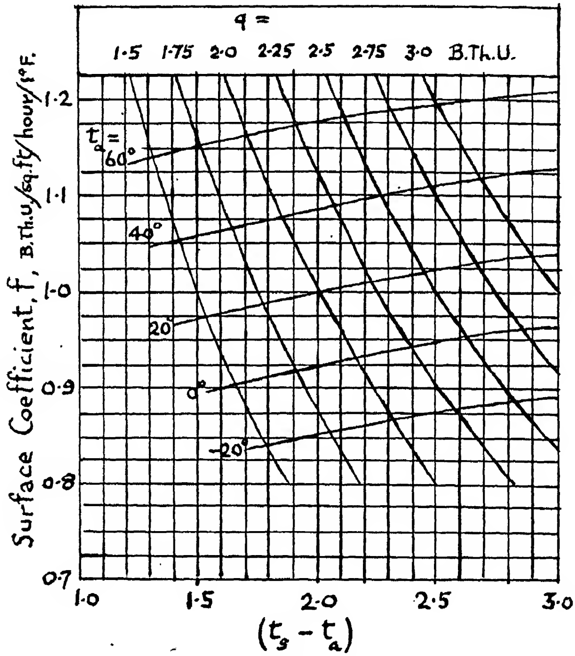


Fig. 9.

zontal surface with the direction of heat flow upwards, and 0·20 for a horizontal surface facing downward.

The appropriate value of **f** must be taken to conform with the rate of heat flow. The equation above indicates that the value of **f**, itself expressed per degree of temperature-difference, increases as the temperature-difference increases. The value of **q** depends upon the total thermal resistance

available to impede heat flow. But in addition $q = f(t_s - t_a)$. This must remain true, while the value of f must also correspond with that of $(t_s - t_a)$ and the position on the temperature scale at which heat flow is occurring. Fig. 9 illustrates the interdependence of these variables for the wall surface inside a cold room.

The rate of heat reception or rejection by convection is increased markedly should the contiguous air be set in forced motion. This occurs on surfaces of buildings exposed to wind. A curve recorded in *Heat Transmission* [5] suggests that allowance for this effect may be made by multiplying the calculated convection transfer for still air by $\left(1 + \frac{v}{3}\right)$ where v is the air velocity in miles per hour. This approximation is sufficiently close for air velocities up to 15 m.p.h. for calculations relating to insulated structures.

Surface Resistance.—This, the reciprocal of the surface coefficient, in some instances makes the major contribution in resisting the flow of heat as, for example, in an unlined building of corrugated iron or a partition of asbestos cement sheets. Comparatively it is of a small order in relation to the thermal resistance necessary to a cold store.

It is notable that the quantity of heat transmitted to or from a surface in contact with a fluid under the influence of a few degrees of temperature-difference, represents the thermal transmission through the insulating structure itself, however thick it may be and of whatever it may consist. Under stable conditions, the temperature at any point in the structure adjusts itself automatically so that the rate of heat flow is constant throughout. If it were possible for heat to accumulate at some point in the insulating structure, the temperature at that point would be raised. This would result in a decreased temperature-difference causing heat flow to that point, and an increased temperature-difference causing heat flow from that point.

Equilibrium would be re-established at once. The foregoing presumes stability of the overall temperature-difference; otherwise the temperature distribution will depend upon the thermal diffusivity of the particular material. When equilibrium has been established, the rate of heat flow at any point in an insulating structure, whether simple or compound, must be the same as the rate of heat flow through the structure as a whole.

Thermal Resistance of Compound Structures.—The insulation of the bounding surfaces of a room or building is rarely a simple homogeneous slab, but is almost always a compound slab built up of several layers of differing materials, including that of the building structure itself. The thermal conductivities of all the particular materials are likely to differ, and if not known, can be determined by experiment. The temperature of the air in contact with the two surfaces is known (t_1, t_2), but the temperature at the planes of junction of the various layers of material forming the slab are not known. Let these temperatures be t_a, t_b, t_c . . . and the thicknesses of the various layers be L_1, L_2, L_3 . . . , having thermal conductivities k_1, k_2, k_3 . . . Let the surface coefficients be f_1, f_2, and considering unit area,

$$t_1 - t_a = q.\frac{1}{f_1}$$

$$t_a - t_b = q.\frac{L_1}{k_1}$$

$$t_b - t_c = q.\frac{L_2}{k_2}$$

. . . . .

$$t_n - t_2 = q.\frac{1}{f_2},$$

the rate of heat flow, q, being the same through each layer of material, as has been shown.

Adding these equations gives—

$$t_1 - t_2 = q.\left(\frac{1}{f_1} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \qquad + \frac{1}{f_2}\right.$$

The summation in brackets is defined as the Total Thermal Resistance of a structure, the word " structure " connoting a multilayer system of an uniformly constructed boundary to a room or building, e.g. an insulated wall or roof. If an air space or cavity exists in the system, an additional surface resistance must be inserted in the summation of individual resistances. In the case of a series of air spaces between partitions consisting of metallic foil or the like, the thicknesses $L_1, L_2, \ldots$ may be so small as to be negligible. The total thermal resistance will then be the sum of a number of surface resistances.

From the above equation,

$$\frac{q}{t_1 - t_2} = \frac{1}{\frac{1}{f_1} + \frac{L_1}{k_1} + \frac{L_2}{k_2} + \cdots + \frac{1}{f_2}} = U,$$

U being called the Thermal Transmittance.

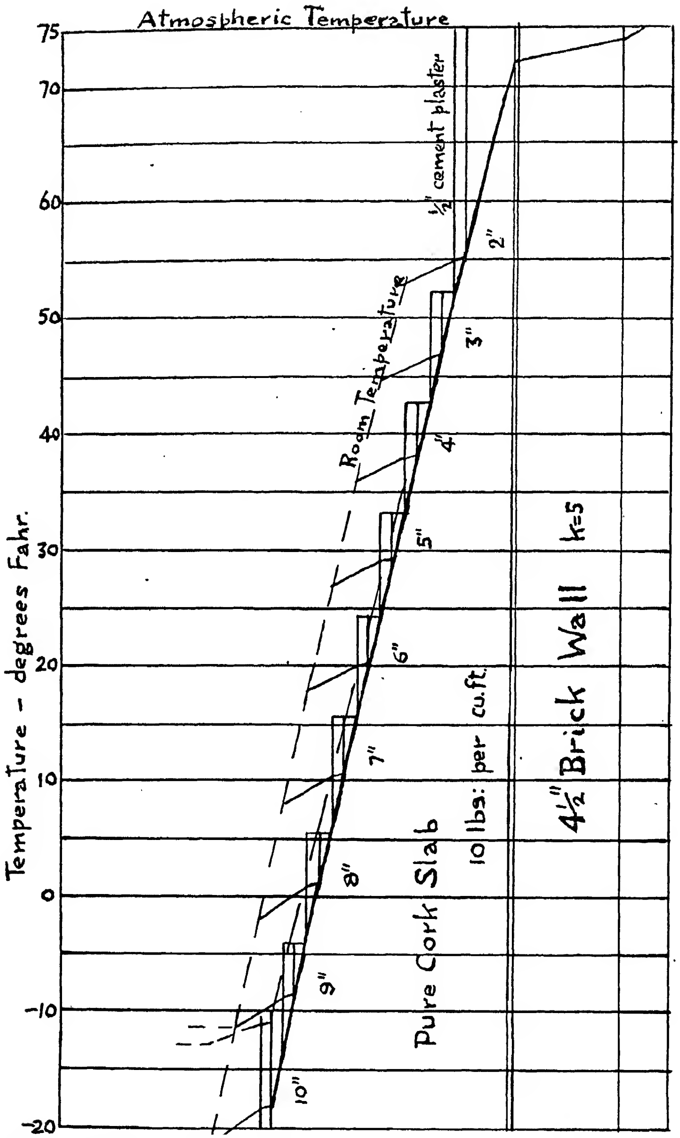
From the foregoing equations it is a simple matter to derive the values of the temperatures at the planes of junction between the various layers of a system and to record the temperature-gradient graphically. The thermal transmittance is first determined, and this gives the value of q for any particular temperature-difference. Inserting this value of q in turn in each of the equations representing the state of heat flow in the several layers, gives the values of $t_a, t_b, t_c \ldots$ The thickness of material which is at a temperature below freezing-point in low-temperature rooms is made clear by such a graph. This domain is important because any access of moisture to it due to cavities or inadequate airproofness results in the formation of ice crystals, with consequent structural and insulative deterioration. More than one layer of insulating material is very advisable from the plane of 32° F. outwards, in order that

all joints may be staggered and so prevent points of freezing temperature from creeping further through the thickness of the insulating material via small gaps in the joints, caused either initially by the human element or subsequently by other means, such as building settlement.

Fig. 10 shows the temperature-gradient through an insulated wall consisting of a single course of brickwork $4\frac{1}{2}$ in. thick, insulated on one face with baked cork slab from 2 in. to 10 in. in thickness, the cork surface being finished with Portland cement plaster $\frac{1}{2}$ in. thick. Cork slab is the material employed most widely as the insulating material for refrigerated rooms. The thicknesses shown cover the whole probable range of requirement for this purpose. The adjustment which may be advisable to take account of different types and thicknesses of building material is referred to later.

The surface coefficient of the inside surface, that of the plaster, has been taken as varying from 1·14 to 0·875 B.Th.U. per sq. ft. per hour per degree F., according to the surface temperature and assuming still air. That of the outside surface, the brickwork, has been taken as 2·56 B.Th.U., on the presumption that a reasonable allowance for air movement would be a wind velocity of 12 m.p.h. The thermal resistance of the two surfaces together amounts to only 0·13 of the total thermal resistance of the 2-in. cork slab specification and to only 0·036 of that offered by the 10-in. cork. Small variation in the figures taken to represent the surface coefficient will make only a small difference to the temperatures calculated. The thicker the insulation is, the less is the proportion which the surface resistance contributes to the total.

For the purpose of illustrating temperature-gradient, the value of **q** embodied in Fig. 10 has been assumed at 2·25 B.Th.U. per sq. ft. per hour, a figure which is fairly representative of accepted practice for structures of this type at the difference of air temperature shown. The



Temperature Gradient for Cork Slab when q = 2·25 B.Th.U/sq.ft/hr.

Fig

F

broken line (straight) represents the temperature gradient incorporating a constant conductivity value of cork slab, as that corresponding with a mean temperature of 65° (**k** = 0·275, see Fig. 1). It has been seen that with cellular materials there is a definite variation of thermal conductivity with temperature. The continuous curvilinear line incorporates a correction on this account, based on the linear function for cork slab shown in Fig. 1. With the object of avoiding obscurity, a single curvilinear line through the appropriate points on the plane of junction of cork with plaster has been introduced, and takes the place of a series of straight lines from each point individually. It will be observed that from the variation of **k** with temperature, benefit accrues of nearly one inch of cork slab in the reasonable domain of 10-in. thickness. In practice, the cost of 1 in. of thickness can be avoided and 9-in. thickness employed instead of 10-in. for temperatures in this region.

By inverting the graph of Fig. 10, information is obtainable at temperatures varying upwards from 75° F., i.e. within the range 75°–172·5° F., up to which latter temperature cork slab is reasonably employable. Specific temperatures are shown in this figure on account of the variation of **k**, the value of **U** depending upon the position of the mean temperature on the temperature scale.

The thickness of brick wall adopted, viz. 4½ in., has been chosen because of its close approximation in value of thermal resistance to other thicknesses of common building materials which are frequently the subject of consideration (see Table VI).

The contribution towards resisting heat flow which is made by building material in general is small in comparison with that made by insulating material. Brick walls of greater thickness offer the appropriate increase of thermal resistance. Table VII gives the percentage reduction in heat flow which results from an additional 4½-in. thickness of brickwork, i.e. a 9-in wall in lieu of 4½-in, and from

TABLE VI

Material	Thickness inches	Conductivity k = (B.Th.U.)	$\frac{L}{k}$
Brickwork	$4\frac{1}{2}$	5·0	0·90
Concrete 1 : 2 : 4 (Gravel aggregate)	6	7·0	0·857
Deal boards	$\frac{3}{4}$	0·81	0·926
Spruce boards	$\frac{5}{8}$	0·70	0·893
Sandstone, Limestone . .	9	10·0	0·90

Table VI can be read the corresponding increase of thickness of other materials necessary to produce the same reduction.

TABLE VII

Thickness of Cork Slab	2″	3″	4″	5″	6″	7″	8″	9″	10″
Percentage reduction in rate of heat flow . .	10	6·9	5	4·3	3·6	3·0	2·7	2·37	2·1

The Reception of Heat by Solar Radiation.—The transfer of heat from air at a higher temperature to a building with which the warm air is in contact is not the only means by which heat transference may occur. Heat may be received in considerable quantity from surrounding buildings and other objects by direct radiation. The most potent source of radiant heat to which a building is subject is direct sunlight. The quantity of heat receivable varies widely and depends upon the degree of absorbency of the atmosphere at any particular time, being greatest when the sky is quite clear. In the winter season the prevailing degree of obscurity of the sky is greater than in the summer season, and it is in the latter that the highest rates of heat reception are recorded.

Solar radiation is measured by the quantity of heat

received on a plane normal to the direction of radiation. Table VIII gives results of tests recorded over 10 years at Kew Observatory.

TABLE VIII.—HEAT RECEIVED BY SOLAR RADIATION [12]

B.Th.U. per sq. ft. per hour							
Jan.	218	Apr.	288	July	298	Oct.	260
Feb.	247	May	298	Aug.	285	Nov.	235
Mch.	276	June	288	Sept.	279	Dec.	209

The number of hours during which solar radiation occurs varies from a minimum on the shortest day to a maximum on the longest. The angle of incidence of the sun's rays on any particular surface varies throughout each day from sunrise to sunset and also from day to day at the meridian.

The obliquity of the ecliptic of $23\frac{1}{2}°$ results in the relative position of the sun becoming vertically above any point in latitude $23\frac{1}{2}°$ N. at the meridian on midsummer day in the northern hemisphere. In any latitude north of this, the direction of radiation never becomes normal to a horizontal plane, i.e. a plane which is tangential to the earth at the particular point on its surface which is under consideration. The maximum rate of heat reception on a horizontal plane, e.g. a flat roof, is given by multiplying by the sine of the angle of incidence.

Thus, $$Q = Q_r . \sin \alpha.$$

In latitude 51° N., in which London is situated, the maximum value of $\sin \alpha$ is 0·887. For other geographical locations the appropriate value of $\sin \alpha$ must be determined.

This value—$Q_r . \sin \alpha$—is that obtaining at the meridian on midsummer day. It represents the maximum rate of heat reception possible at the particular location taken. The actual value of Q_r at this time depends upon the clarity of the sky, and the figures of Table VIII suggest a

value of $\mathbf{Q_r}$ = 300 B.Th.U. per sq. ft. for the purpose of calculations relating to insulated structures. Reference to meteorological records reveals that higher figures are recorded on rare occasions, but that the average value is considerably lower (see Appendix I). This quantity would be that received by a perfectly black body, and further adjustment becomes necessary in that none of the materials used in ordinary building construction possesses an emissivity value as high as unity.

The rate of heat reception by radiation depends upon the quality of the surface of the body. Polished metals such as silver, copper and aluminium reflect most of the radiant heat incident upon them and have an emissivity in the region of 0·05, as compared with unity for a perfectly black body. The emissivity of ordinary building material, such as brick, concrete and asphalt, is in the region of 0·9, and on this basis the quantity of heat received by a horizontal surface becomes

$$\mathbf{q = 0{\cdot}9.Q_r.\sin\alpha} \text{ B.Th.U. per sq. ft. per hour.}$$

In latitude 51° N. this would be $\mathbf{0{\cdot}9.\ 300.\ 0{\cdot}887}$

$$= \mathbf{240}, \text{ say.}$$

Similarly the maximum rate of heat absorption by vertical surfaces occurs when the angle of incidence on them is greatest. The latter depends upon the orientation of the particular building and will occur at the time of the year in which, according to the angle of declination of the sun, the rays are most nearly normal to the plane of the particular wall, but the quantity depends on whether the sky is clear or obscured. The time of exposure to radiation of walls facing east or west is but half that of a horizontal surface and, further, the greatest angle of incidence occurs at the times of the day when heat reception from the atmosphere is less than when, during the middle of the day, the atmosphere has reached a higher level of temperature. In addition, contiguous buildings may provide complete

shade, or adjacent buildings may provide partial shade, during the period of maximum angle of potential incidence.

Walls facing south will (in the northern hemisphere) be exposed to radiation for a longer period of time than walls facing east or west, but in the summer season the angle of incidence on such walls is always small. The total surface receiving heat at any time is represented by the projection of the building on a plane normal to the direction of radiation. Walls facing north may usually be neglected, and for the remaining walls it would appear reasonable to adopt a factor of one-third the quantity received by a flat roof, based on the maximum projected area of the exposed walls.

Masonry and concrete forming the shell of a building act as a reservoir of heat in which the quantity of heat is varying continually. The temperature of the air in contact with a flat concrete roof (for example) is rising during the early hours of daylight. The rate of heat reception is increased as the sun ascends and the angle of incidence of radiation increases. The continued reception of heat raises the temperature of the concrete in accordance with the density, thickness and specific heat of the material forming the slab, while at the same time heat is being rejected at a low rate through the insulating material into the building. When the continued reception of heat by solar radiation has raised the surface temperature of the roof above that of the atmosphere, the roof slab commences to reject heat to the air in contact with it at a rate commensurate with the difference of temperature existing at the particular moment. At the point of time of maximum surface temperature, the rate of heat reception is balanced by the rate of heat rejection into the building via the insulating material and to the atmosphere in contact with it—the stationary temperature indicating that the heat quantity of the reservoir is, for an interval of time, also stationary. Here occurs the maximum temperature-difference with which the insulation must contend.

Assuming that the atmospheric temperature in contact with the roof is 75° F. at this time—a temperature which, in these latitudes, would be attained only under still atmospheric conditions—and considering, for the sake of illustration, a constant room temperature under the roof of 35° F. with a corresponding Thermal Resistance of the insulated roof of $\left(\mathbf{R} + \frac{1}{\mathbf{f}_2}\right) = 17{\cdot}3$, the equation can be written—

$$0{\cdot}9.\mathbf{Q}_r.\sin\alpha = \frac{t_{sm} - 35}{17{\cdot}3} + (t_{sm} - 75)f_1,$$

where t_{sm} = the maximum outside surface temperature,
f_1 = the outside surface coefficient, and
f_2 = the inside ,, ,,

The lower the value of f_1 the higher will be the value of t_{sm}. The value of f_1 is not likely to be less than 3 B.Th.U. per sq. ft. per 1° F. with a temperature-difference between roof and atmosphere of the order of 60–70°, coupled with air movement which on the roof of a building will rarely be as low as 2 m.p.h. Therefore, under the condition that

$$\frac{t_{sm} - 35}{17{\cdot}3} + (t_{sm} - 75)3 = 240,$$

the value of t_{sm} is 153° F.

The rate of heat flow through the roof is

$$\frac{153 - 35}{17{\cdot}3} \text{ or } 6{\cdot}33 \text{ B.Th.U. per sq. ft. per hour.}$$

The calculated value of $\mathbf{q}$, if difference of air temperature only is taken into account, is 2·26.

Seeing that air movement on the roof of a building will rarely be as low as 2 m.p.h., it is evident that when the value of f_1 is increased due to increase of wind velocity, or if the atmospheric temperature falls, the surface temperature of the roof slab will fall owing to increased rate of heat rejection. Similarly the presence of insulating

material impedes heat rejection from the underside, and if this were removed the surface temperature would not rise so high. Other conditions remaining the same, suppose the value of **R** taken above is reduced to 2·37 by the omission of insulating material, the maximum surface temperature would then be 140° F. The rate of heat rejection to the atmosphere is considerably greater than the rate of heat flow through the roof slab when the efficiency of insulation is reasonable, and therefore small variation of the thickness of the insulating material will not alter the surface temperature to any great extent. On the other hand, the amount of increase in heat flow due to solar radiation over that due to difference of air temperature is not so great if the inside building temperature is low, coupled with thermal resistance appropriate to it for the same thermal transmittance. Substituting in the equation above a temperature of $-$ 12·5° to represent that inside the building, together with a value of **R** = 38 (which with an outside temperature of 75° F. gives the same value of **q** = 2·26), the maximum heat flow through the insulation is

$$\frac{153 + 12{\cdot}5}{38} = 4{\cdot}36 \text{ B.Th.U. per sq. ft. per hour.}$$

The maximum rate of heat flow which has been considered occurs only at midday or shortly after and will not be maintained for any length of time. The heat flow may be 90 per cent. or more of the maximum over a period of about 3 hours and over 50 per cent. for an additional 5 hours. The advisability of providing increased thickness of insulating material on a flat roof of a cold store is obvious. The allowance for extra duty on account of solar radiation which may be considered reasonable must be viewed in the light of the duty which it is anticipated will be required from the plant during the period when the increased insulation "loss" occurs. If the full output of the plant is required for process duty during the hours when solar radiation

imposes its greatest effect, it may be reasonable to increase the thickness of roof insulation, indicated by the temperature-difference of outside and inside air, by an amount up to 50 per cent. The corresponding increase of thickness on walls exposed to radiation would not exceed 25 per cent. Conditions of duty vary widely according to the purpose to which the particular room is put, and the insulation "loss" ranges from practically the whole refrigerating duty, as in the case of an ice-store, down to a small fraction of the duty, as in the case of a room for chilling meat. The margin of output possessed by the particular plant which is available, or is proposed for use, should also be considered.

There is a simple expedient which combats effectively the reception of heat through solar radiation to which the flat type of roof is so exposed. This consists in flooding the roof with water to a depth of $1\frac{1}{2}$–2 in., maintained by a ball valve or other means. Evaporation from the surface of the water prevents any considerable rise in temperature, which in practice is not likely to reach 100° F. The simplicity of this device has an added appeal in that a much more constant temperature is secured for the asphalt topping to withstand. The importance of this is increased in the case of a cold-store, in that the reduced heat flow through insulation results in higher surface temperatures of the asphalt than would occur on buildings used for other purposes (see Appendix II).

A pitched roof offers more obstruction to flow of heat than a flat roof by virtue of the air "cushion" between it and the ceiling forming the attic space. Omission of this ceiling surrenders the advantage. The obstruction is most effective if the attic space is well ventilated to the atmosphere, since the roof temperature will be higher than that of the air. If the attic space is completely enclosed, the accumulation of heat will raise the temperature of the air, but suitable ventilation enables the heat to be removed by simple interchange of air. In other words, the roof provides

"shade" for the ceiling, although some heat flow will remain through radiation from the roof to the ceiling.

Variation of Area with Constant Capacity.—The insulation of a room for constant-temperature purposes frequently involves the utilization of portions of an existing building and in some cases the adaptation of an existing room *in toto*. Where an entirely new structure is contemplated, option may usually be exercised in the shape of the room proposed. The smaller the boundary area can be made in relation to the cubic capacity required, the smaller will be the insulation "loss." There are many geometric forms which might be considered, the majority of which are of academic interest only, and of little or no practical value. Asymmetry of shape involves inconvenience of operation for most purposes. Vertical walls are regarded as essential, curved surfaces are more expensive to erect and insulate, and, generally, departure from orthodox layout provides at least as much disadvantage as advantage. The intensity of loading on floors, suspended or otherwise, reaches a figure of 3 cwts. per sq. ft. in many requirements of cold storage and tends to confine the design of such buildings to orthodox lines.

Where freedom of choice exists, the height of a constant-temperature room is determined from the purpose to which it is to be put. Rooms used for storage purposes require a height greater than that of a tall man and not much greater than the height to which an ordinary man is able to manipulate boxes, bales, and so forth. The hanging of carcases for chilling purposes may demand greater height, which in the case of beef reaches 13–14 ft. Superimposition of large tanks in brewery work may call for a greater dimension still. The determination of the height from these considerations leaves variation of cubic capacity to accord with the area of the floor.

Let $\mathbf{x}, \mathbf{y}$ be the horizontal dimensions of the room and let $\mathbf{xy} = \mathbf{A} =$ constant. The area of the ceiling and floor,

then, is constant and the area of the walls is $2h(x + y)$. Writing this as equal to A',

$$A' = 2h(x + y)$$

$$= 2h\left(x + \frac{A}{x}\right)$$

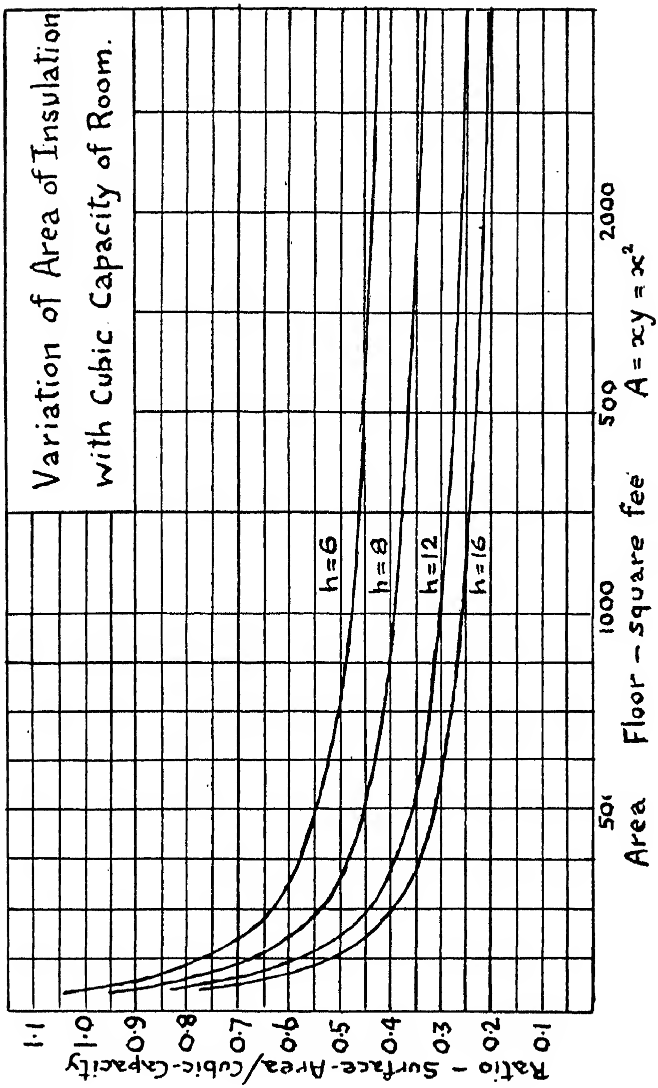
$$\frac{dA'}{dx} = 2h\left(1 - \frac{A}{x^2}\right)$$

whence, on equating to zero, the well-known result is obtained that A' is a minimum when $x = y = \sqrt{A}$. This condition incurs the minimum area of insulation required for a given capacity of room of rectangular shape and fixed height, with the corollary of minimum initial cost and rate of heat flow, when shape is considered as the only variable. The total area of surface to be insulated is $(4hx + 2x^2)$ and it is obvious that doubling the height h doubles also the cubic capacity but increases the surface area to only $(8hx + 2x^2)$, which is always less than $2(4hx + 2x^2)$. Unnecessary height will never result in economy, even though a relative saving is made available. On the other hand, if three rooms of equal size are required, it would be a measure of thermal economy to design the rooms as true squares, arranged one above the other. Reasonable requirements of architecture must overrule such arrangements, and as the height of the rooms is predetermined, the horizontal dimensions must not be so out of proportion with the total height as to prejudice soundness of structural design. The optimum arrangement from the point of view of insulation is not of such importance as to transcend all other considerations; for example, the provision of a lift would be avoided if space were available for all the rooms to be on the same level. In a later chapter is discussed the possible arrangement of building details which enables an external envelope of insulation to enclose a space subdivided internally to provide convenience of operation.

Fig. 11 shows the optimum values ($x^2 = A$) of area/volume ratio for rooms of fixed height. The area taken is the nett area of insulating material which is required to be purchased to form the envelope, and the thickness of material has been presumed as 6 in. This area does not coincide with that on which calculation of heat flow should be based, owing to the effect of thickness at the rectangular junctions of the vertical and horizontal surfaces, although the difference is not great where the value of each dimension is large in comparison with the thickness of insulating material.

Cursory consideration of two constant-temperature rooms of different cubic capacity, but under all other conditions exactly similar, would lead to the assumption that the rate of change of temperature-difference which commences immediately the source of heat addition or extraction is discontinued, would be the same for both. The other conditions referred to as being similar include insulation of similar type, thickness and conductivity, building structure of similar detail, the same temperature-difference and position on the temperature scale, and the same heat capacity per unit of cubic capacity. The curves shown in Fig. 11 illustrate the wide difference which can occur between two such rooms. To take two examples, a room 6 ft. high with floor area of 49 sq. ft. will undergo twice the rate of change of temperature-difference as a room of the same height but of floor area 900 sq. ft.; and the rate of change of a room of 294 cu. ft. capacity ($h = 6$) is no less than five times greater than that of a room of 40,000 cu. ft. ($h = 16$). It is important to note that these comparisons are made on the basis of equal heat capacity per unit of cubic capacity—a basis which seems inevitable to a fair comparison of the behaviour of insulated rooms.

These curves provide also an indication of the variation of insulation cost—both first cost and that ensuing through heat loss day by day—in relation to the potential earning capacity of the room. Storage in cold rooms used for the



Variation of Area of Insulation
with Cubic Capacity of Room.
h=6
h=8
h=12
h=16
Area Floor – square fee
A = xy = x²
50
1000
500
2000
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
Ratio – Surface-Area/Cubic-Capacity

FIG. 11.

preservation of food is costed on a basis of weight of produce stored and length of time during which it is held. Within limits, the cubic capacity of such rooms is a direct measure of their potential earning capacity.

Variation of Area with Shape.—The possible variation of surface area in relation to any given capacity can be considerable. So far, consideration has been confined to the optimum shape of floor, i.e. a square. In practice it is more the exception than the rule for circumstances to be so favourable as to make the attainment of the optimum shape a matter of no difficulty. Indeed, buildings and rooms approximating to the ideal are unusual.

Presuming again that $xy = A =$ constant, where x, y are the horizontal dimensions of a rectangular room of height h, the variation in surface area is that occasioned by the walls, as x and y differ numerically from each other.

The area of wall insulation is

$$[2(x + L) + 2(y + L)](h + 2L),$$

assuming L, the thickness of insulation, to be the same on all surfaces. In order to obtain figures for comparison, it is necessary to adopt a value for L. In the curves shown in Fig. 12 a thickness of 6 in. (0·5 ft.) has been taken.

The wall area is now $2(x + y + 1)(h + 1)$ or per unit height $2(x + y + 1)$.

Let the minor dimension of the room, y, be some fraction, n, of the major dimension x. Thus $y = nx$, and since $xy = A$, where A is the inside ceiling area, $nx^2 = A$.

The wall area per unit of height is then

$$2x(n + 1) + 2,$$

$$= 2\sqrt{\frac{A}{n}}.(n + 1) + 2$$

which is a minimum when $n = 1$, i.e. when the four sides are equal.

Fig. 12 shows the variation of wall area per unit of height from $\mathbf{n} = 1$ to $\mathbf{n} = 0{\cdot}2$. In small rooms the condition $\mathbf{y} = \mathbf{0{\cdot}2x}$ is improbable owing to the inconvenience in working a room of this shape. With a floor area of 50 sq. ft.

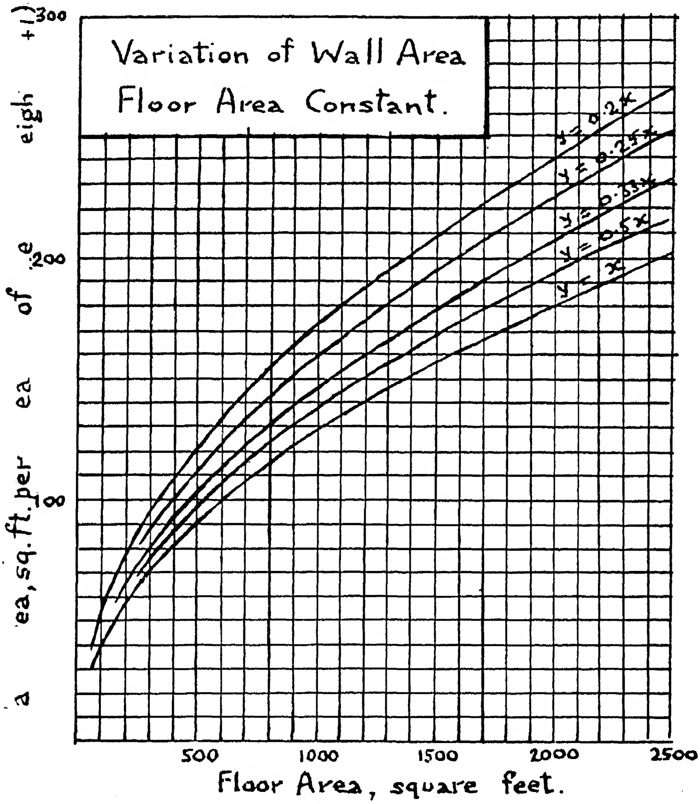


FIG. 12.

this would mean that $\mathbf{x} = 16$ ft., $\mathbf{y} = 3$ ft. $1\frac{1}{2}$ in. Such a shape can be employed usefully as a warming or cooling tunnel. Still longer tunnels than this in relation to width are used for the cooling of sweets and biscuits after enrobing

with chocolate. But in such a process the element of time takes pride of place in importance, because the tunnel must be sufficiently long for the required degree of plasticity to be eliminated with the prescribed speed of conveyance through the tunnel and the degree of heat extraction available. A comparison may be made with the drying tunnels used to accelerate the application of half-a-dozen or more coats of paint to the bodies of mass-produced motor vehicles.

Rigid pursuit of the optimum shape is, then, neither always possible nor desirable. In the last two examples the heat duty of the process is high in comparison with the insulation loss, and, provided that the efficiency of insulation is adequate for the process to function properly, there is no good reason for sacrificing all other considerations to the ideals of thermal insulation.

With large rooms and buildings, the condition $\mathbf{y} = \mathbf{nx}$, where $\mathbf{n} \neq 1$, is usual, and the increase in area of insulation involves both increased cost of installation and increase in total insulation "loss" per hour. The latter tends to increase the rate of change of temperature-difference when the heat plant is at rest and to shorten the intermission periods.

The percentage increase of about 30 when $\mathbf{y} = \mathbf{0{\cdot}2x}$ indicates the relatively uneconomic shape of such a building, and only the exigencies of site limitation should induce its adoption.

Equivalent Mean Area of Insulation of Rectangular Spaces.—Shape Factor, $\mathbf{S}$, is defined by the equation $\mathbf{q} = \mathbf{k.S(t_{s_1} - t_{s_2})}$. Distortion of the lines of heat flow near the edges and corners is caused by the thickness of the boundaries of insulated rectangular enclosures, and the shape factor $\mathbf{A/L}$ of a flat slab is not applicable to calculation of the total heat flow into a room as a whole. Identification of the laws of electrical conduction with those of thermal con-

duction has enabled use to be made of experiments on the electrical flow lines in an electrolyte. An equation for shape factor has been deduced from such experiments by Langmuir, Meiklejohn and Adams, and on account of apparent variation in result according to the relative magnitude of the thickness of insulation and the internal dimensions, three empirical formulae have been propounded.[10]

(1) When all three dimensions are greater than $0{\cdot}2L$,

$$S = \frac{A}{L} + 0{\cdot}54\Sigma l + 1{\cdot}2L,$$

where $l =$ sum of lengths of edges $= 4(x + y + h)$.

(2) When one dimension is less than $0{\cdot}2L$,

$$S = \frac{A}{L} + 0.465\Sigma l + 0{\cdot}35L.$$

(3) When all three dimensions are less than $0{\cdot}2L$,

$$S = 0{\cdot}79\sqrt{AB}$$

where B is the external area, A being the internal area.

The two latter conditions refer to small boxes and are of minor importance in the field of insulated structures. The units in these equations are required to be consistent, i.e. the thickness, L, must be taken in feet, and the conductivity must be adjusted to correspond with 1 ft. as the unit of thickness instead of 1 in. Equation (1) is applicable to insulated buildings and rooms since, in practice, L rarely reaches a value of 1 ft. and is coupled with internal dimensions several times this amount, even in small-capacity rooms. The last term, $0{\cdot}2L$, is very small in most cases, and it is only under the conditions of equations (2) and (3) that it would become relatively large. Formula (1) then ceases to apply.

The importance of the variation of this calculated area from the arithmetic-mean area can be visualized in part from the graphs of Fig. 11. As the superficial area decreases in relation to the cubic capacity, so will variation of the

calculated area decrease in importance. Fig. 13 shows the variation of area as given by formula (1) from the internal area, **A**, for a height of 7 ft. and for three values of **L** based on the optimum shape of floor. The arithmetic-mean increment of area is $\frac{\mathbf{B - A}}{2}$ whereas the increment of

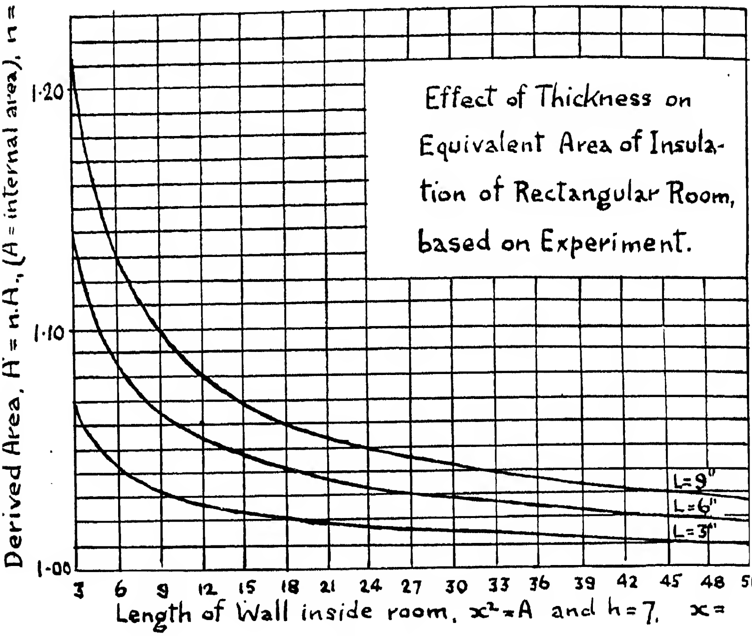


FIG. 13.

equivalent area as given by formula (1) approximates closely to $\frac{\mathbf{B - A}}{4}$. The percentage increase of **A** is less for smaller thicknesses of insulation than for greater and, for a given value of **L**, decreases as **x** increases.

Rate of Change of Temperature-Difference.—When the source of heat addition or extraction operating on a constant-

temperature room is cut off, the temperature-difference which has been created and maintained artificially immediately commences to decrease. The heat flow from the domain at the higher temperature to that at the lower would continue until equalization occurred, unless the heat plant, or some other outside source, intervened to maintain a difference of temperature. The rate of change of temperature-difference depends upon the rate of heat reception, or loss, by the contents of the room, as the case may be, and upon the heat capacity of the contents and of the insulated structure itself, per unit of temperature. The former depends upon the efficiency of insulation, but the latter may vary widely according to the weight and nature of the contents at the particular time considered.

The heat capacity of an empty room may be represented only by that of the insulating and fixing materials. In most cases this will be supplemented by a system of piping of one sort or another, together with the contents of the pipe, which causes the heat addition or extraction. That of the air contained in the room is small, since 1 lb. of air occupies a volume of about 13 cu. ft. at normal barometric pressures, and has a specific heat of only 0·238 B.Th.U. per lb., neglecting water vapour.

On the other hand, the heat capacity per unit of temperature may be considerable where a room is filled to its reasonable limit with materials of high specific heat, examples of which are provided by the storage of ice or butter. Considering butter as an illustration, this material is usually packed in rectangular boxes which can be stored conveniently and with smaller loss of space than ensues with many other objects of storage. The proportion of the gross cubic capacity of a room which it is reasonable to apply to actual storage may be as high as two-thirds for this particular material, varying according to the size and shape of the room. The maximum weight of butter per cubic foot gross storage space is about 25 lbs., and with a specific heat

value of 0·58 B.Th.U. per lb., the heat capacity per unit of temperature becomes 14·5 B.Th.U. per cu. ft. for this material. This can now be re-expressed in terms of 1 sq. ft. of insulation by reference to the area/volume ratio of the particular size of room. The curves shown in Fig. 11, with suitable correction where $\mathbf{n} \neq 1$ in the relationship $\mathbf{y} = \mathbf{n.x}$, present a guide in this respect.

TABLE IX

Commodity	Weight per cu. ft. gross of Storage Space lb.	Specific Heat	Heat Capacity. B.Th.U. per °F. per cu. ft.
Ice	40	0·5	20·0
Butter (boxes) . .	28	0·58	16·25
,, (casks) . .	22	0·58	12·76
Lard (boxes) . . .	26	0·45	11·7
Beef, Mutton, Lamb (frozen)	17–19	0·65	11·3–12·6
Yeast	19	0·90	17·1
Bacon (bales) . . .	18	0·36	6·5
,, (bales, frozen) .	18	0·26	4·67
Cheese	10	0·64	6·4
Furs	—	—	1·0

Table IX gives figures for the heat capacity per cubic foot of gross storage-space of several commodities handled in low-temperature rooms. The figures take into account inevitable loss of storage-space occasioned by the irregular contour of some of the commodities listed, and a proportion of the total capacity which it is necessary to leave for gangway space and other considerations. From these figures may be calculated the heat capacity per square foot of insulation for any particular size and shape of room.

In the majority of cases the heat capacity of the pipe or other system which provides the heating or cooling effect is high enough to be taken into account and, indeed, is

designed to be so in cases where the heat capacity of the particular object of storage is known not to be adequate to obviate quick change of temperature-difference. An example of this may be cited in the provision of a brine evaporator tank in small cold rooms in order to retard the rate of temperature rise and to ensure intermission periods of sufficient duration for convenience of attendance. Automatic control of the plant has largely superseded this device, but similar tanks are employed where the duty of heat extraction alternates between light and heavy, as in the milk store of a dairy. In this arrangement, the additional heat capacity created during the period of light duty is utilized to accomplish part of the heavy duty when this, in turn, is required.

The heat capacity of the insulated structure itself is not great. Referring to Fig. 10, it will be observed that the brick wall is nowhere at a temperature far removed from that of the atmosphere. The major portion of the temperature-difference occurs in the insulating material, and as this is of low weight and moderate specific heat and as, in addition, it is the mean temperature which is of concern, the contribution of the structure to heat capacity is not large. By calculating the temperatures at the planes of junction of the layers of material forming the insulated structure for the normal working overall temperature difference, and again for a temperature-difference corresponding with a chosen rise of room temperature, the heat absorbed by the structure is easily derived from a knowledge of the specific heat and mean temperature rise of each of the different materials. Table X gives the heat capacity, per unit of temperature rise of the air within a room, for cork slab and two loose-packed materials. Although the specific heats of the two latter differ markedly, so also do the densities, and for all practical purposes they may be ranked as equivalent. No allowance for moisture content has been made. The presence of moisture increases the heat capacity,

but at the same time increases the conductivity, and that which is gained on the one side is lost on the other.

TABLE X.—HEAT CAPACITY OF INSULATION

(B.Th.U. per sq. ft. per 1° F. change of room temperature)

Wall	Cork Slab (plaster finish ½-in. cement mortar)			Slag Wool or Granulated Cork (⅞-in. spruce board finish)	
	2-in.	5-in.	10-in.	6-in.	12-in.
4½-in. Brickwork	2·0	2·4	3·0	2·0	2·6
9-in. ,,	2·8	2·9	3·2	2·4	2·9

The two thicknesses of loose-packed material given in this table correspond in thermal transmittance with the two larger thicknesses of cork slab given. In practice an additional 1 in. and 2 in. respectively would be considered necessary to equivalency to allow for some moisture absorption. The comparatively small effect of the heavy building material will be noted, due to the relatively small change of temperature which it undergoes.

During the first element of time after the heat plant ceases operation, the quantity of heat flowing through the insulated structure is that corresponding with the original temperature-difference. The reception or rejection of this quantity of heat by the contents of the room causes a rise or fall of its temperature, as the case may be, according to the available heat capacity per unit of temperature. The temperature-difference causing heat flow is thereby decreased, and during the next element of time the quantity of heat flowing, and the consequent further recession of temperature-difference of the contents, are both less than in the first element. And so on until the temperature-difference is infinitely small, presuming constancy of temperature of the atmosphere.

Let **H** B.Th.U. be required per square foot of insulation to raise the temperature of the contents of the room through 1° F., and let θ be the overall temperature difference (equals $t_1 - t_2$).

Then, for a small increment of time, δn,

$$H.\delta\theta = -\frac{\theta}{R}.\delta n,$$

where **R** is the thermal resistance of the insulated structure; whence

$$n = -H.R.\log_e \theta + C.$$

Let θ_0 be the initial temperature difference when $n = 0$, then

$$C = H.R.\log_e \theta_0$$

and

$$n = H.R.\log_e \left(\frac{\theta_0}{\theta}\right) \text{ hours.}$$

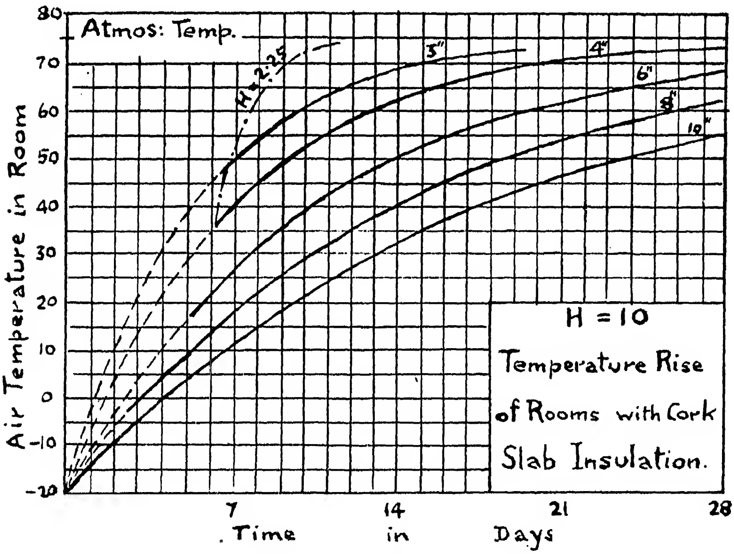


FIG. 14.

This equation is expressed graphically in Fig. 14, taking $\theta_0 = 95$ to correspond with $R = 42{\cdot}2$ for 10 in. cork slab ($q = 2{\cdot}25$), and $H = 10$ B.Th.U. per 1° F. per sq. ft.

The earlier portion of this curve is nearly a straight line, i.e. when the change of temperature is small in comparison with the initial temperature-difference and θ_0/θ is still not far from unity; and an approximation to the temperature change may be calculated quickly as follows. By simple proportion, the initial heat flow of 2·25 B.Th.U. per sq. ft. per hour when $\theta = 95$ is reduced to 2·01 when θ becomes 85° F. The arithmetic mean is $\mathbf{q} = 2{\cdot}13$. A 10° change of temperature when $\mathbf{H} = 10$ involves a total heat flow of $\mathbf{Q} = 100$ and $\mathbf{Q}/\mathbf{q} = 100/2{\cdot}13$ or 47 hours, which is in error by $1\frac{1}{2}$ per cent.

It is in the early part of the curve that interest lies in the majority of cold-store applications, and the approximate method of calculating temperature rise will probably be considered adequate in most cases. It is useful where the rise of temperature does not exceed some 10 per cent. of the initial temperature-difference.

Cold rooms in which are stored articles of very low heat capacity, such as furs, are likely to be subject to rapid change of temperature when the plant is at rest. This will be obvious if a value of $\mathbf{H} = 2{\cdot}5$ is assumed, the time required for a given temperature rise being one-quarter that shown on the curve which is based on $\mathbf{H} = 10$. Thus, in spite of a high degree of insulating efficiency ($\mathbf{q} = 2{\cdot}25$), a rise of some 12° F. may occur during an intermission period of 12 hours. For any other value of $\mathbf{H}$, the number of days given by the curves in Fig. 14 must be multiplied by $\mathbf{H}/\mathbf{10}$.

The curve is shown as being continuous, and this is true where only sensible heat is concerned. Where frozen produce is involved, the curve will be broken at the temperature of freezing appropriate to the particular commodity, at which temperature the curve will follow a straight line parallel to the axis of $\mathbf{n}$. The length of this line would represent the time required for the amount of heat flow at this particular temperature-difference, which is necessary to

satisfy the latent heat of fusion. The curve would then continue in the same form as before, but with a new value of **H** on account of change in the value of specific heat.

An initial temperature-difference of 95° F. has been taken for the purpose of this graph, which is sufficient to include all normal conditions in this country. The continuous portion of each curve commences at the temperature-difference corresponding with a value of $\mathbf{q} = 2{\cdot}25$. At all points on the discontinuous portions the value of **q** is greater, and on a comparative basis the particular values of **R** would not be considered adequate for the temperature-differences corresponding with these portions. Any point on the curve in which the value of **R** is appropriate may be taken as the starting-point, in which case both time and temperature rise must be measured from that point as though it were the origin. Adjustment for other values of **R** for a given value of **H** (10 in this graph) and a given temperature-difference may be made by simple proportion, since **n** varies directly as **R.**

The instantaneous distribution of heat throughout the contents of the room which must be presumed in the foregoing is never entirely true, as there must exist a difference of temperature for heat flow to occur. In practice, there may be a variation of 2 or 3 degrees of temperature in different parts of the room. The graph, however, indicates the fundamentals of the problem, from which the value of **H** emerges as a dominating factor in rate of temperature change, in spite of efficiency of insulation. Inspection of the equation reveals the real function of insulating material in impeding flow of heat, and illustrates the true quality of temperature as being merely an indicator of relative heat quantity.

In cold-stores generally the permissible variation of temperature is small and may be as low as 0·5 F., although in most cases 3° F. would not be unacceptable. The rate at which room temperature rises is of interest from the

points of view of testing the efficiency of insulation, and of possible breakdown of the plant. In connection with frozen produce, it provides indication of the time which would elapse before thawing-out commenced. It is of particular interest in the transport of hot or cold materials in insulated containers to which no heat plant is attached, and in the success of which the element of time plays such an important part.

It has already been noted that the heat capacity per cubic foot of gross space may approach the possible maximum, for any particular commodity, in insulated vans and tanks. The size of the container affects the matter directly, and the value of **H** increases with decrease of the area/volume ratio. Thus the maximum rate of heat flow which can be permitted in order to conform with prescribed temperature limits can be calculated, and the specification of insulation determined accordingly. Considerations of weight and of earning capacity as a function of space available restrict the thickness which it is reasonable to employ, and the efficiency of insulation is, as a rule, lower than that deemed necessary for store rooms. Road and rail vans are subject to direct solar radiation, and the surface coefficient is considerably increased by the higher velocity of air incident on the outside surface, due to the speed at which they travel.

An example of an insulated road van will serve to illustrate the difficulties of variableness which beset the designer. In such a case it is hardly possible for practice to coincide with calculation, but nevertheless calculation is necessary to provide a starting-point. When a fleet of vehicles is in commission, systematic observations will provide necessary data applying to the particular circumstances of operation; but subsequent alteration of insulation due to wide error in the first place is likely to be both expensive and inconvenient.

For the purpose of illustration, the internal dimensions

of the van body will be taken as 11 ft. × 5 ft. × 6 ft., giving a cubic capacity of 330 cu. ft. and an equivalent boundary area of 312 sq. ft. The construction of the body is assumed to be $\frac{1}{8}$-in. hardboard lining inside and outside, with a layer of cork slab 2 in. thick sandwiched between. This gives a value of $\mathbf{R} = 7{\cdot}65$, allowing a high surface coefficient ($\mathbf{f} = 8$ B.Th.U.) for the outside surface on account of the velocity of air caused by the motion of the van. Solar radiation may affect three of the six boundaries at a time. The outside surface temperature, allowing for the heat received by radiation, is not likely to exceed 100° F. when the vehicle is in motion, owing to the increased rate of heat rejection to the atmosphere, the temperature of which is taken at 75° F. Herein lies a source of possible error, as during such times as the vehicle must necessarily be stationary, the outside surface temperature will rise, and given the necessary length of time, a temperature of about 130° F. might be attained. The temperature will fall as soon as the vehicle is set in motion again. The value of $\mathbf{f}_1$ would be much increased in the case of an express goods van on the railway. The value taken above corresponds with a vehicle speed of 15–20 m.p.h. under still atmospheric conditions. Here, again, air speed may vary widely in spite of constant road speed, the effect of greater air speed being to increase the rate of heat reception from the atmosphere but to decrease heat reception from solar radiation.

Suppose that the load to be carried is frozen meat and that the weight per cubic foot is 20 lbs. when the van is filled to capacity. Then if the specific heat is 0·65, the value of $\mathbf{H}$ is $20.0{\cdot}65.\frac{330}{312} = 13{\cdot}75$ B.Th.U. Suppose also that the temperature of the meat on completion of loading is 18° F. and that the rise must not exceed 4° F. at the point of delivery. Then if all six faces were exposed to solar radiation, the number of hours which would elapse

before the specified temperature rise occurred would be given by

$$n = 13 \cdot 75.7 \cdot 5. \log_e \frac{82}{78}$$

$$= 5 \cdot 14 \text{ hours} ;$$

and if all six faces were subject to heat flow due to atmospheric temperature alone, the time would be—

$$n = 13 \cdot 75.7 \cdot 65 \log_e \frac{57}{53}$$

$$= 7 \cdot 77 \text{ hours.}$$

The direction of travel relative to the position of the sun is varying continually, and the general direction from point to point is not specified. The actual time will be intermediate between these two figures, and to obtain a general figure the arithmetic mean of 6·45 hours may be accepted.

If a particular journey under consideration cannot be completed in this time, the conditions of transit specified cannot be fulfilled unless the thermal resistance of the insulation is increased. Obviously it is possible to increase the value of **R** considerably, but both initial expenditure in construction and tare weight are increased, with an accompanying decrease of cubic capacity available as storage-space, and consequently of earning capacity.

A further important point revealed by these calculations is that if the van is only half full, the time available is only half that for a full load. After a reasonable value of **R** has been adopted as the limit, it is apparent that recourse to some heat plant (such as ice and salt) will become necessary with extension of time of transit.

It is interesting to consider the possible alternative of commencing the journey at nightfall, so avoiding the effect of solar radiation and securing a lower atmospheric temperature with which to contend. If the nocturnal atmospheric temperature is taken as 60° F., the time available to fulfil the conditions given is increased to 11 hours—a period which would run into daylight on the succeeding day.

Apart from the exigencies of the road, a margin of safety is very desirable. The maintenance of airtightness with working of the body of the vehicle, due to irregularity of road surface, demands close attention, since cold air is only too readily lost from an exposed container of this type under a large difference of temperature and subject to wind pressure externally. Further, produce in contact with the sides and floor of the body will undergo a greater rise of temperature than that well removed from them, and some proportion of the load may exceed the specified temperature rise, even though as a whole the condition is fulfilled.

Insulated tanks for the transport of pre-cooled milk or pre-heated oils, etc., are, as a whole, in a more favourable position than insulated vans and trucks, because the weight carried is usually greater. A value of $\mathbf{H} = 60$ is not unusual for a full tank.

The efficiency of insulation necessary to prevent freezing in water tanks provides a similar type of problem. It is not always appreciated that if the atmospheric temperature remains below freezing-point it is only a matter of time before freezing commences, unless either the water is changed or heat is applied. The rate of heat loss by the water is reduced to a point which may provide an extension of time six or more times that which is available to the tank without insulation, but unless outside intervention occurs nature is not to be frustrated, but simply impeded, by the use of insulation.

Since it is intended that water tanks should be used for their appropriate purpose, the usual problem is simply that of providing a margin of safety from close of work at night to commencement of work the following morning, or the longer period from midday on Saturday to Monday morning. As a rule the problem is capable of simple solution under normal winter conditions in these latitudes. Water tanks provided for the purpose of emergency supply, or where use is intermittent for any reason, call for careful consideration

of the possible necessity of some means of heating when exceptional conditions demand. With small tanks, the simplest method of restoring heat quantity is to run the water until it is completely replaced and thereby start again, as it were, from scratch. Omission to do so within the period allowed by the particular thermal resistance of the insulation, under the prevailing atmospheric conditions, will result in failure. As with buildings, the greater the capacity of the tank, the greater will be the value of **H** if a constant level is maintained, and therefore the greater will be the margin of safety in terms of time.

Water-supply pipes to tanks, in which the level is controlled by a ball valve, and which normally stand full, are likely to prove a more difficult problem than the tank itself, owing to the low value of **H**. The smaller the pipe the shorter is the time-margin available, for a given efficiency of insulation, and resort to draining may be advisable under extreme conditions.

The Comparative Cost of Insulation.—The cost of heat flow is determinable. In the case of electrical heating it will consist of the cost of electrical energy plus a proportion of the cost of the heaters, cables, switches, etc., and of the installation of them, depending upon the number of years they are expected to last. Similarly, for refrigerating plant, the cost of heat extraction can be calculated from the running costs, attendance and maintenance costs, and a proportion of the initial cost of the whole plant on the basis of the whole being paid off in a reasonable number of years. These costs will vary widely according not only to the heat duty required, but also to the temperature at which the duty must be performed. Increase in the size of plant tends to decrease the cost per B.Th.U. extracted, whereas reduction in the pressure of evaporation tends to increase the cost. This may range from 1,000–5,000 B.Th.U. per penny.

The annual cost of the plant will usually be deemed to

be in the region of 15–20 per cent. of the initial cost of installation, including allowance for depreciation, replacements and interest on capital. To this must be added the annual running cost in energy or fuel, oil, attendance, refrigerant, repairs, etc., and from an estimate of the total B.Th.U. extracted per annum is computed the cost of heat extraction per 1,000 B.Th.U.

Heat flowing into the room must necessarily be re-extracted, and since the heat flow per square foot of insulation is known, the cost of this heat flow per square foot can be calculated per annum or per hour. The initial cost of the insulating material per square foot is also known. Here, again, some fraction of the first cost of installation represents the annual cost of the insulation. This is likely to be rather less than the proportion required for the machinery, provided that the insulating material and method of erection are of a permanent character. About $12\frac{1}{2}$–15 per cent. will generally be considered adequate.

The flow of heat into the room costs money for its re-extraction, since there is no means of insulation providing 100 per cent. efficiency, and to this is added the cost of providing the insulation. The presence of the insulating material reduces the amount of heat flow, and it is the sum of the costs of this reduced heat flow, and of the insulation itself per unit of time, which will now be considered.

It is required to find the thickness of any given insulating material which will secure the minimum cost of heat "loss" per annum. The quantity of heat flow, and therefore its cost, is a function of the thickness $\mathbf{L}$. The initial cost of the particular material is also a function of $\mathbf{L}$.

Let $\mathbf{Q}$ = the heat flow per square foot per annum (B.Th.U.);

$\mathbf{p}$ = cost per 1,000 B.Th.U. (pence); and

$\mathbf{R'}$ = the thermal resistance of the materials, other than the insulating material, forming the structure.

Then $$\mathbf{Q} = \mathbf{q.24.365}$$

$$= \frac{}{\mathbf{R' + L/k}}.\mathbf{8760},$$

where $\mathbf{k}$ is the thermal conductivity of the insulating material.

The cost per square foot per annum is $\frac{}{\mathbf{1000}}.\frac{\theta}{\mathbf{R' + L/k}}.\mathbf{8760}$

$$= \mathbf{8{\cdot}76p}.\frac{\theta}{\mathbf{R' + L/k}} \text{ pence.}$$

Let $\mathbf{m}$ be the cost of 1 sq. ft. of the particular insulating material per inch of thickness, and let $\mathbf{G}$ be the initial cost of labour and material necessary for erecting and finishing per square foot (e.g. plastering, tiling, boarding and painting).

The overall cost of the heat " loss " per square foot per annum is

$$\mathbf{f(L)} = \mathbf{8{\cdot}76.p}.\frac{\theta}{\mathbf{R' + L/k}} + \mathbf{d(mL + G)},$$

where $\mathbf{d}$ is the fraction of initial cost assigned as representing the annual cost.

Both these terms are functions of $\mathbf{L}$. Differentiating with respect to $\mathbf{L}$ gives

$$\mathbf{f'(L)} = -\frac{\mathbf{8{\cdot}76p.\theta.k}}{\mathbf{(k.R' + L)}} + \mathbf{d.m},$$

whence, on equating to zero,

$$\mathbf{L} = \sqrt{\frac{\mathbf{8{\cdot}76.p.\theta.k}}{\mathbf{d.m}}} - \mathbf{R'k}$$

which is a minimum.

In order to view this matter in its true perspective, it is necessary to plot the equation of $\mathbf{f(L)}$. A typical series is shown in Fig. 15. Variation of θ, the temperature-difference appropriate to a particular value of $\mathbf{p}$, may be considerable, but is not likely to extend to the whole range of curves shown. In general, the higher the value of $\mathbf{p}$, the greater will be the temperature-difference applicable

to it. For a given temperature-difference, **p** will vary according to the size of the plant. The overall cost of insulation **f(L)** increases with the temperature-difference. Whatever alternative thickness is explored, the fact remains

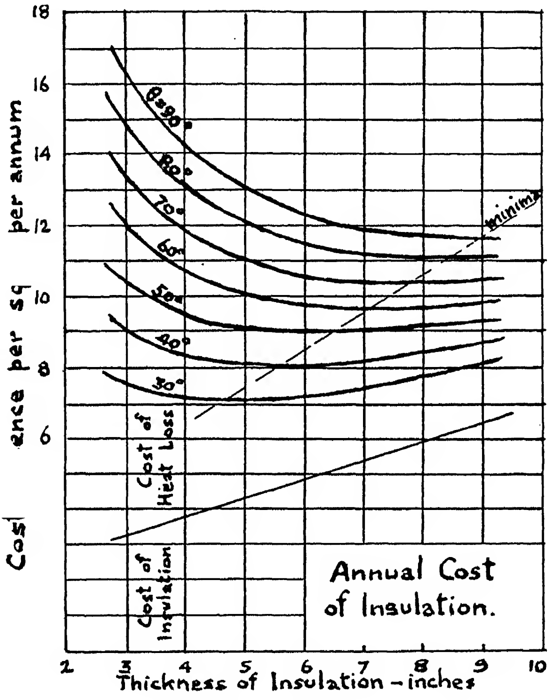


FIG. 15.

that the greater the temperature-difference, the greater will be the overall cost per square foot per annum for any given size of room and for the same basic costs.

The second term in the equation for the value of **L** is usually small, as **R′** is small, as a rule, in comparison with the value of **R** for the whole structure. It will be observed that the number of years' purchase assigned to the insulation

materially affects the result. The arbitrary nature of this assignment and of that involved in the derivation of the value of **p** suggests restraint in the practical application of this matter. It is important to realize that, from the point of view of cost, there is an optimum thickness, and that wide deviation from it will not constitute sound practice under normal industrial conditions.

Plotting the curves discloses an important point which is not evident from the equation of **f(L)**, i.e. that although there is a particular thickness (not necessarily integral) corresponding with the minimum cost, the curve is sufficiently flat at this point for thicknesses of (**L** + 1) and (**L** − 1) to justify consideration, owing to the small difference in annual cost for these values. A thickness (**L** − 1) involves a reduced capital outlay coupled with increased rate of heat flow, whereas a thickness (**L** + 1) does not increase the annual cost to any great extent, although increasing the initial cost. The latter, however, secures the advantage of reduced heat flow in connection with intermission periods and the effect of possible breakdown of the plant. It is clear that a higher initial purchase price may prove to be real economy, apart from other advantage accruing. The logical consequence of increased running time is increase of the arbitrary estimate of cost per annum of the machinery, since there must be direct reference between the number of years' purchase and the total running time which constitutes the life of the plant. The possibility of justifying a smaller plant by means of increasing the thickness of insulation should not be overlooked. It will be the more readily present where process duty is small and insulation "losses" constitute the major part of the total heat duty.

Safety Factor.—It is usual for a factor to be applied to calculated results to make allowance for possible variation in practice of the data on which the calculations are based. In the case of thermal insulation, variation may occur both

with material and workmanship. Slab cork in bulk may show variation in density which, for a given quality of cork, will affect the thermal conductivity. The tolerance in density should not exceed $\pm$ 0·5 lb. per cu. ft. In the manufacture of the slabs the relative proportion of coarse and fine granules is difficult to maintain with exactitude. Selection of the virgin cork does not eliminate entirely variation in quality of the raw material used. The time and temperatures of the baking process and the subsequent machining to thickness have been brought to a high level of consistency in material obtained from any particular source. Broken edges or corners of the slabs may occur through careless handling. Slabs may not be butted tightly (jointing material is not considered desirable) and joints may not be staggered correctly. Misalignment of a row of slabs, resulting in a gap between adjacent rows, is not likely with good machining and correct butting of the units. It is possible for cork slabs laid on shuttering to become displaced during pouring of the concrete unless correctly positioned. With experienced workmanship, variation due to the human element on site will remain very small, and a safety factor of 1·2 should be adequate to cover the foregoing contingencies. With inexperienced workmanship, the heat flow may be considerably increased by discontinuities of slabbing, but the worst trouble to be anticipated in low-temperature rooms is likely to be structural rather than thermal—that is, impairment of the insulating material through ingress of moisture or through the eruptive effect of ice-formation in cavities.

Where the continuity of the insulation is interrupted by timbers required to carry a finishing surface of asbestos cement sheets or tongued-and-grooved boarding, due allowance should be made for the increased heat flow through the area in which timber occurs and, in addition, the safety factor may reasonably be increased to 1·5 or more. The accuracy of butt joints between the slabs and the timbers,

and of the making airtight of such joints, is more easily secured in the case of the small type of room sectionally built in a works than in the case of larger rooms insulated on site. The employment of an internal surface finish which necessitates timber grounds for rooms maintained at temperatures below freezing possesses an element of hazard.

In the case of loose-packed insulating material such as slag wool (silicate cotton), granulated and regranulated cork, it is usual for a factor of safety to be incorporated in the determination of the thickness required. Thus a 6-in thickness of these materials is considered comparable with a 4-in. thickness of cork slab. There are two reasons for this. Firstly, the penetration of the insulation by the timber grounds necessary to carry the boarding or other retaining diaphragm results in increased heat flow at a large number of points aggregating some 10–12 per cent. of the total area. As the thermal conductivity of timber is 3 to 4 times that of the insulating material, the increase in thickness is justified by the improved insulation at these points and the reduction of the temperature-difference between the surface and the air in contact with it. On the latter depends the readiness for precipitation of moisture from the air. The second reason is the very real difficulty in making retaining constructions sufficiently airtight to prevent access of moisture. Even brickwork, unless treated internally with a waterproof rendering applied either by brush or trowel, is porous to some degree. When quite dry, the thermal conductivity of these loose-packed materials is comparable with that of cork slab, but the practical difficulty of maintaining them in a dry state when subject to internal convection currents makes it advisable to assume that the conductivity will be increased by the water taken up. Recent endeavours to waterproof fibrous materials have met with some success. This relies on the coating of the fibres with a greasy material such as wax, so defeating the capillary attraction for moisture possessed by all loose fibrous material.

Slag wool can be damaged easily by too much pressure, and it is possible for this to be caused in transit. Inexpert placing of the wool in position may cause considerable variation in density and therefore in conductivity. Too light packing allows unnecessary space for convection currents, whereas too heavy packing breaks down the cellular formation of the fibres and increases the conductivity. The positioning and jointing of the usual waterproof paper and tongued-and-grooved boards which retain the wool, particularly at the junctions of the various boundaries, can vary according to the degree of care and experience of the erector. The last applies also to granular materials such as granulated cork.

The packing of granulated and regranulated cork is simpler than that of slag wool, since the granules do not break down with undue pressure. The possibility of variation lies mainly in the quality of the material and, in common with all other similar material, in the airtightness of the retaining walls, whether of brick or stone masonry, timber, or other material. In applications where normal retaining methods are pursued, it is perhaps simpler to adopt a value of **k** for use in calculations some 25–33 per cent. greater than that for perfectly dry material, and so represent a mean value of a factor which, under average practical conditions, probably exhibits continuous deterioration at a low rate throughout its useful life.

With this provision, the factor of safety may be of the same order as that for cork slab, assuming that provision is to be made for making good any voids which may be caused through settlement of the insulating material in the course of time.

CHAPTER IV

STRUCTURAL DETAIL IN RELATION TO INSULATION—REFRIGERATED BUILDINGS

The design of buildings intended for the application of insulating material is not quite the same problem as that of light independent structures. Probably the majority of constant-temperature installations consist of a single room inside an existing factory or other building. This class may be divided into two sections: (*a*) those involving the acceptance of an existing room with or without modification of detail, and (*b*) those involving the erection of an independent structure within a larger room.

An additional, intermediate, section incorporates some requirements of both the above. It will be sufficient here to discuss the two types separately.

The other class of constant-temperature installations consists of buildings erected solely for the purpose, and in which detail of design peculiar to the requirements of insulation may be exploited without hindrance. This class ranges in size from a single-storey building of one room to large buildings of several storeys and a number of rooms. The degree of compromise tolerable in existing features of rooms coming under section (*a*) of the first class will be indicated by consideration of buildings included in the second class, while independent ceilings (as distinct from load-carrying floors) provide a problem similar in most respects in both sections (*a*) and (*b*).

The shape of a building is determined largely by the particular site available and is modified by the height of the various floors, necessary for the particular purposes to which they are to be put. Consideration should be given

to the incurrence of the smallest reasonable area to be insulated in obtaining the cubic capacity required, as has already been seen. If some portion of each floor is not to be insulated, but is to be left as handling or office space, the external wall abutting such space should be arranged to face the direction most exposed to solar radiation, in order to reduce as far as is practicable the temperature load with which the insulating material has to contend.

The increasing density of air with reduction of temperature indicates the advisability of having the room of lowest temperature in the basement or on the ground floor, as the case may be, and the room of highest temperature immediately under the roof. This arrangement locates the increased temperature-difference which is caused by solar radiation at the place where the amount of temperature-difference otherwise is least, and where it can be taken care of by a reasonable increase in the thickness of insulating material applied to the roof. The rooms of lower temperature also will have the benefit of whatever shade there may be available from adjacent buildings. The rate of heat flow downwards through the intermediate floors when the surface of higher temperature is above the lower is less than when the temperature position is reversed. The probable small temperature variation of one or two degrees between the air against the ceiling of a room and that against the floor assists rather than resists.

The optimum position for a cold-room is no doubt below ground level, with all walls and floor abutting on earth and with the only means of access via a trap-door in the floor above. Thus the immediate reception of heat by solar radiation is prevented, and the natural interchange of air caused by density change with temperature does not occur. This condition is found in some small plants in shop premises and occasionally in brine tanks sunk below floor level. The natural coolness of the ordinary dry cellar is an indication of this advantage. A cold-room located on an upper floor

above floors used for other purposes and which will be consistently at a temperature as high as or higher than that of the atmosphere, will suffer an increased insulation "loss" through the floor. Consideration should be given to the advisability of increasing the thickness of insulation at this point, remembering that goods in the room may be in direct contact with the floor and therefore that heat flow to the goods is facilitated. The proximity to a cold-room of an engine room, boiler house or chimney flue, is evidently undesirable. Considerations of convenience may demand compromise in these matters, but at increased expense either of insulation, or of running and ease of control of the plant.

Airlocks.—It is not considered reasonable for the temperature-difference between the air in a cold-room and the ambient air to exceed about 45° F. without the interposition of an airlock to cover the door. The greater the temperature-difference, the greater is the readiness of the contained air to interchange with that outside owing to difference of density. The arrangement of a small enclosed handling space provided with a second door prevents the direct interchange of air which otherwise would occur on a large scale each time the door is opened. While the heat "loss" itself is of importance, the effects of the precipitation of moisture when the warm moisture-laden air outside comes into sudden collision with very cold air, is of still greater importance. When the door of a cold-room is shut, the inside surface of the door is at the same temperature as the air contained within the room. As soon as the door is opened, this surface, together with that of the door frames, is exposed to the warmer air outside and receives a certain amount of moisture through condensation. If the temperature of the air in the room is below freezing-point, the moisture remains there in the form of frost and is increased in quantity with each operation of the door. It is not

unusual for this to result in inability to close the door at all, or extreme difficulty in opening owing to welding of the frost on the frames and door returns through pressure. Time allowed for defrosting by natural means is rarely tolerated, and scraping is often overlooked until too late.

An antechamber or airlock may be desirable for a room operating at a temperature as high as 36° F. if it is situated in a building in which the humidity regularly runs high, due to some process which is pursued there. Although actual frosting may not occur, the absorption of moisture by the timber of the door inevitably results in swelling and probable jamming of the door. It is for this reason that the old type of tight-fitting door with bevelled frames has given way to a more modern design in which an original clearance of about $\frac{1}{4}$ inch is incorporated to allow for change of size through variation of the moisture content of the timber. The air seal is then made on planes which are normal to the direction of motion when contact is made, with soft rubber gasket as a resilient contacting material.

Doors.—The timbers usually employed for cold-store doors include Columbian and Oregon pine and Red deal. For temperatures below freezing it is preferable to use Pitch pine or Teak on account of the better resistance to moisture absorption and swelling. The last two involve an increase in cost which is amply justified where the room temperature is zero F. or below. Actually the conductivity of Pitch pine and Teak is higher than that of Deal and Spruce, but the increase of insulation loss through the relatively small area of a door is of no account in comparison with the advantage of reluctance to change of shape. The difficulty of making cold-store doors waterproof by means of a film of paint or varnish is real, and it is not uncommon for a door plug 3 ft. in width to increase by as much as $\frac{1}{4}$ in., particularly if faced with boards. The more arduous the duty, the greater is likely to be the amount of swell, since,

for a given humidity of the atmosphere, the quantity of moisture precipitation on the timber depends upon the amount of temperature-difference between the timber and the atmosphere. It is an advantage to coat with shellac varnish each individual piece of timber before assembling a door, and the grooved joints of boards may be made with red lead, wherever very low temperatures are required to be withstood. The placing of cold-room doors in an external wall of a building unprotected from the atmosphere is a somewhat hazardous undertaking, and trouble is more probable than not. Timber readily accepts moisture from, and returns moisture to the atmosphere in contact with it, and to expose the timber of a close-fitting and airtight door to the alternations of fog, rain and possibly direct solar radiation constitutes a provocation of nature which is not likely to succeed. The most unpretentious measure of easement desirable for such a door involves the provision of an ordinary type of door immediately covering the insulated door. By this means some protection is offered from the never-ceasing change from diurnal to nocturnal atmospheric conditions and from the extremes of seasonal variation. Wherever possible, cold-room doors should be well removed from outside doors and openings in the buildings in which they are situated, in order to obtain as great a constancy of humidity as the particular conditions of service may allow.

Airlocks used in conjunction with rooms operating at temperatures below freezing should be insulated with a thickness of material not less than that corresponding with half the temperature-difference to which the room itself is subject. Where an airlock is found desirable for a room temperature above freezing-point, it is of greater importance that this should be airtight rather than insulated, since the exclusion of moisture-laden air is its main object. Airlocks attached to rooms at zero F. or below should have a cooling system of their own, with the object of directing most of

the condensable moisture to it and preventing it ruining the efficiency of the inner doors. This cooling system, more often than not, is omitted on the score of cost with, in many cases, dire results. Some ice-cream rooms at a temperature of about $-10°$ F. become almost unworkable because of such omission, particularly if limitation of site enforces too close proximity of the inner and outer doors. With unorganized handling, a similar result can occur at temperatures 25° higher.

The construction necessary to form an airlock may form part of the building structure, but more usually it is formed by independent means. In large multi-roomed buildings, space is economized by arranging one airlock to cover the doors to three or four rooms, and in such cases a permanent type of wall, such as brick, is desirable owing to the weight of insulated doors.

Building Material.—Both the layout and the proposed size of the building may affect the choice of building materials. Broadly defined, materials of greater density possess greater structural strength and also higher thermal conductivity than lighter materials. In general, the sphere of usefulness of each individual material is limited to the exercise of the particular function which is its most prominent feature. Consequently it is necessary to employ material of high density, such as brick and concrete, to form a building structure on normal lines, but modified in view of subsequent installation of insulating material. It is not the purpose of this treatise to pursue in detail the architectural calculations required, but simply to indicate desiderata.

The loading of intermediate floors in multi-storied buildings varies according to the purpose to which the building is to be put, but for ordinary cold-storage purposes is above the average at 3 cwt. per sq. ft. The reasonable span of floor between supports is limited to about 10–12 ft. in large rooms, and resort to stanchions becomes unavoidable. When

available insulating material was confined to loose-packed granular or fibrous substances such as charcoal, granulated cork and slag wool, it was the usual practice to employ joists of timber, boarded above to form a floor and below in order to retain the insulating material in place between the joists. The relatively low thermal conductivity of timber in comparison with other building material justified this arrangement, which it was found necessary to apply to walls as well. The ideal of insulation permits no insection of its continuity, and the interposition of timbers which extended through the whole thickness produced areas where the rate of heat flow was some three times that through the remainder of the boundary. The advent of solid material in slab form, capable of being erected without retaining constructions or other kind of outside support, proved to be a valuable step forward, and one which was congenial with improvements in building construction which were developing on ferro-concrete lines.

The housing of a concrete floor slab in a masonry wall imposed the necessity of continuing the insulation inwards from the walls on both the upper and lower surfaces of an intermediate floor. Although that on the underside might be discontinued reasonably at a distance of a few feet from the wall, almost invariably it proves inconvenient to do this on the upper side, owing to the break in floor level which it entails. An alternative method of carrying the floor at the wall line provides stanchions placed immediately inside the walls to support the main beams and obviates direct contact between the concrete floors and the walls, usually of brick. Curtain walls are erected clear of the stanchions, allowing only sufficient space for the particular thickness of insulating material required between the face of the wall and the concrete casing of the stanchions. This casing is poured after the insulating material, cork slab in the great majority of cases, has been fixed. Curtain walls are tied at the level of each floor—an essential precaution with

buildings of any height—but these steel ties are alone in penetrating the envelope of insulation which otherwise is continuous from ground level to roof. In this design it is usual for the roof to be a concrete floor similar to the intermediate floors, and with only stanchions for its support. The insulation is then laid on top, being continuous with the wall insulation and covered with asphalt to protect it from the elements.

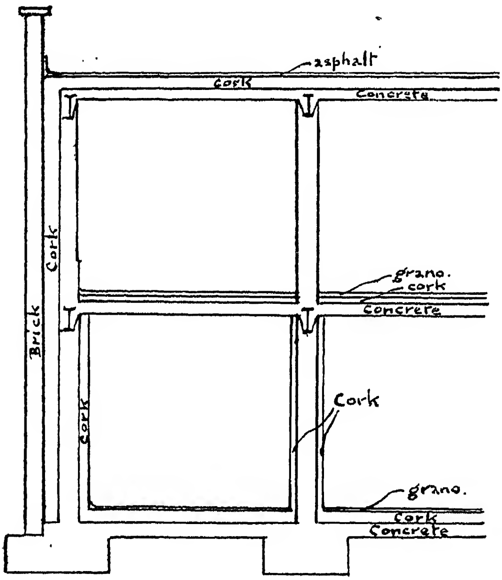


FIG. 16.—ENVELOPE TYPE OF INSULATED BUILDING

This arrangement obviates the necessity of insulating the stanchions, with the exception of those on the ground floor. The latter are in direct contact with the earth via their foundations, since it is not possible to interpose insulating material on account of the variable loading. The insulation of these stanchions should extend up to the ground-floor ceiling, and be not less than two-thirds the wall insulation

in thickness. This thickness of building material in feet compares in thermal resistance with a similar number of inches thickness of insulating material, and therefore there is no necessity to continue insulation beyond this point. Intermediate floors may require insulating lightly if different temperatures are to be maintained on the various floors. In this case the insulating material is preferably laid on the upper side of the floor, as this avoids the expense of additional insulation which would be required for the vertical sides of the beams which carry the floor. In the design of a new building there is little difficulty in arranging suitable floor levels.

Exposed beams below a concrete or other floor should be avoided wherever possible. This is not always possible in buildings of ordinary design, particularly if of more than one storey. If the floor incorporates timber joists, some or all of the projection of the main beams can be avoided by carrying the joists on the lower flange of the beam instead of the upper. An unbroken ceiling is obtained by this means. If, however, the load and span to be carried enforce a depth of beam greater than the reasonable depth of joist required, and the joists are to be boarded over for use as a floor, it will not be possible for the main beams to project above the floor, and projection from the underside is inevitable. Similar projection occurs with concrete floors of the precast hollow-beam and of the reinforced hollow-tile varieties. Floors of mass concrete can be improved by carrying the secondary R.S. joists on angle irons riveted to the web of the beam, and by this means housing the upper part of the beam in the thickness of the concrete floor. Haunching of R.S. beams is desirable in cold-storage work, as this is effective in excluding air from contact with the high-conductivity steel and so preventing the possibility of frost formation or moisture condensation. The haunching may be of the boxed (rectangular) type in which some 2 in. of concrete is carried below the lower flange, or of the

tapered type in which the concrete stands on, and is flush with, the lower flange. Fire regulations of local authorities may compel resort to the former type, but the latter is more to be recommended on account of the greater simplicity of lining the formers with insulating material (e.g. cork slab) prior to the concrete being poured. Both the usual two layers of material are carried around the beam, instead of the first layer being largely wasted in filling the recess between the flanges of an unhaunched beam. With timber floors carried on the upper flange of the R.S. beam, either the recesses must first be filled with insulating material, or alternatively the haunched type of beam may be imitated by wedging or bolting timber grounds between the beam flanges. This device ensures continuity of the two-layer principle by bringing the insulation line outside the exposed beam flange, but it leaves an air space between the web of the beam and the insulating material. Air spaces of this nature are preferably avoided, as it is difficult to guarantee the absence of minute faults through which filtration of air may occur.

Casing of rolled steel stanchions with concrete, as for beams, is preferable to leaving the steel exposed, although this sacrifices some room space. Stanchions adjacent to the curtain walls of the envelope type of insulated building should be encased, using formers only for the exposed sides and utilizing the wall insulation to complete the temporary sheathing. Lightweight concretes are suitable for this purpose, and further reference to this type of material will be made later. If not filled with concrete, the recesses between the flanges should be filled with insulating material, either solid or loose-packed. Stanchions which are not to be insulated should always be encased.

A modified form of envelope insulation is possible in buildings of two or more storeys which can be covered by a single span of pitched roof. The width of such buildings is not likely to exceed 30 ft., but even so, with a length

of about 100 ft., a total capacity in the region of 50,000 cu. ft. is available from two storeys. In this design the roof principals are designed to form the supports for a ceiling, consisting usually of timber joists resting on the steel trusses. It is not possible to introduce concrete owing to the great weight, but with a joist span between neighbouring roof principals of some 12 ft. there is no difficulty in carrying an insulated ceiling of about 24 lbs. per sq. ft. Since there will be no overhead loading, timber joists of 6 in. $\times$ 2 in. are sufficient to carry the insulating material and finish. The suspension of direct-expansion grids, which represent both a standing and a moderate loading, is also a reasonable possibility with the substitution of a few larger joists at the points where the additional loading occurs.

The walls may be steel-framed with brick panelling or may consist simply of brickwork. The intermediate floor needs to be carried on centre as well as wall stanchions, owing to the span, and these are insulated to their full height. The floor itself may be of any usual construction. If the whole of the ground floor is to be held at one temperature and the whole of the first floor at a higher temperature, a thickness of insulating material adequate to cope with the temperature-difference is laid on top of the intermediate floor. Under these conditions, and presuming that internal partition walls are not required for further subdivision of the space, it may be considered convenient to carry the intermediate floor directly on the walls, and not on stanchions adjacent to the walls. This results in economy of building, and the direct contact of the intermediate floor with the walls is countered by means of "ribbon insulation." This device consists in applying a ribbon of insulating material to the underside of the intermediate floor for a width of from 4 to 6 ft. inwards from the walls, that is, for a distance which provides a somewhat similar rate of heat flow inwards through the floor structure as through the insulated wall. Ribbon insulation is not

entirely successful for timber floors carried on R.S. beams, owing to the spaces between the timber joists and the impossibility of fully insulating the beams. A timber plate secured to the top flange of the beam on which the timber joists rest is the best that can be done, and special detail

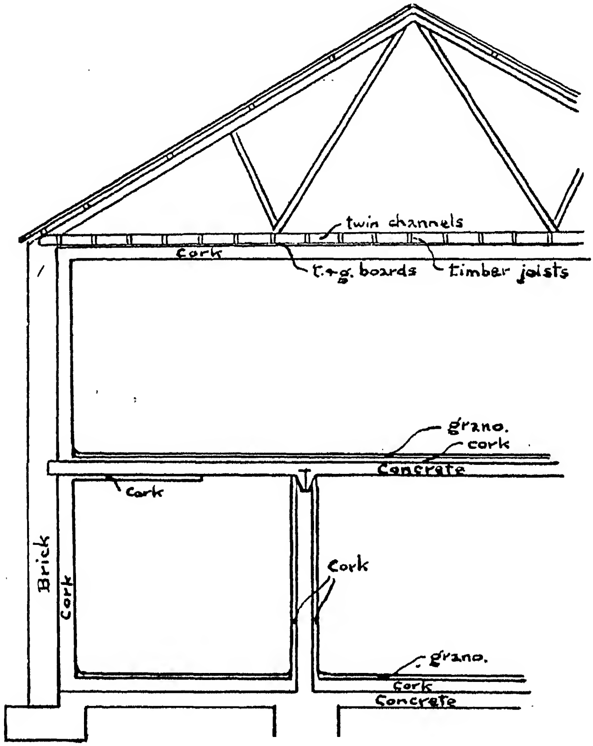


FIG. 17.—RIBBON INSULATION AND SUSPENDED CEILING

is necessary where the timber joists lie normal to the plane of the wall. With concrete floors requiring shuttering, the insulating material needs to be erected after the shuttering has been struck, and it cannot be laid prior to the concrete being poured owing to difference of shuttering level.

The thickness of ribbon insulation should not be less than

half that of the walls, and for temperatures below 25° F. should consist of two-layer work so as to avoid any possibility of structural rupture through frost formation. The same applies to the insulation laid over an intermediate floor, and in this connection it should be borne in mind that occasions arise when, for reasons of defrosting or repairs, one of the rooms may undergo a considerable rise in temperature. At such periods, though no doubt transitionary, the floor insulation may be stressed more heavily than would be considered reasonable for normal practice. Therefore the thickness should be somewhat greater than that indicated by the prevailing temperature-difference alone.

Double-skin Roofing.—The attic space of a pitched roof, with the advantage it possesses of increased resistance to the reception of heat by solar radiation, can be imitated, where it is desired to retain a flat concrete roof, by forming the roof as a double skin. Virtually, this device involves the provision of two roof slabs, separated by a distance of 3 or 4 ft. With the object of avoiding troublesome shuttering, it is useful to form the upper slab of precast concrete beams with the usual waterproof topping. The interspace should be well ventilated. At first sight this arrangement would appear to involve an increased height of building solely on this account, but in practice it is often easily arranged. Unnecessary height is avoided in cold stores, as there is no point in increasing the insulation loss unless there is a corresponding return on the credit side. Thus, for most purposes, a clear height of from 6 ft. 6 in. to 8 ft. is considered ample. This height would not be considered sufficient for offices and workrooms in the same building as the cold store, and so the general layout of the building is not materially altered by the incorporation of a double roof over some portion of it.

In the adaptation of an existing room as a cold store, it is quite the rule for the existing height to be unnecessarily

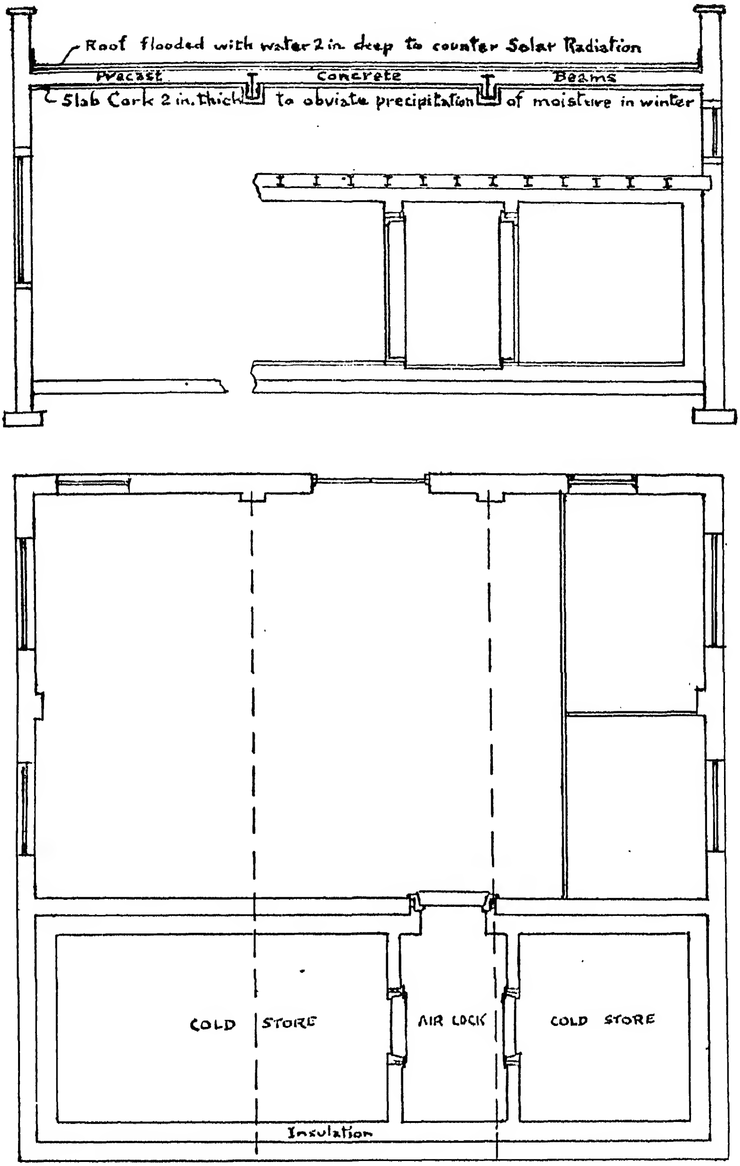


FIG. 18.—ELEVATION AND PLAN OF TYPICAL SMALL FACTORY WITH COLD STORES WITH DOUBLE-SKIN ROOFING

great and for an independent ceiling to be constructed below the existing one. This possesses the added advantage of simplifying the arrangement of supports in positions suitable to carry whatever suspended load may be proposed, such as rail layouts for meat storage and hangers for direct-expansion grids. Further, it may assist in avoiding troublesome drilling of concrete or the cutting of cavity floors, such as those incorporating hollow tiles.

Omission of Floor Insulation.—A device is sometimes employed in the insulation detail of ground-floor rooms such as are used for bacon-curing purposes at a temperature of about 45° F. This consists in carrying the wall insulation from the wall footings some 18–24 in. below the floor level instead of from the upper surface of the base concrete. This assists in reducing the heat flow to the base concrete, since the source of this heat flow is, in the end, solar radiation. Insulation is then applied normally to the walls and ceiling but omitted from the floor.

It is usual for this arrangement to be applied only to rooms of large floor area, say, 2,000 sq. ft. and upwards, as the greater the distance from the walls the less is the rate of heat flow to the floor from beneath. Therefore, with a large floor area of normal shape, a major proportion of the area is but little affected by the absence of insulation at a temperature in this region. The ground temperatures shown in Fig. 6 were recorded in ground which was exposed and not screened from solar radiation by a superimposed building.

Hot Surfaces.—The insulation of hot surfaces in buildings, such as the brickwork of a chimney flue, requires careful consideration. If comfort temperatures only are the object, an application of a good heat-resisting composition direct to the brickwork may be adequate. The thickness is not likely to exceed $1\frac{1}{2}$ in. and some kind of metal reinforce-

ment, independently secured to the brickwork, is necessary. Such an arrangement will not be adequate for temperatures normally much below atmospheric. In the case of new building, special insulating bricks may be incorporated in the brickwork forming the structure of the flue, and if this arrangement would result in a surface temperature inside the room still higher than that desirable for the particular purpose, a single leaf of brickwork may be erected 2 in. clear of the flue to obtain a cavity. If the cavity can be vented to the atmosphere so much the better, but it must not be vented to the room.

If the room is a cold store, the above precautions would be supplementary merely to the normal insulation appropriate to the particular temperature to be maintained. The usual insulating material is then erected to the inside face of the single-leaf wall. The latter may involve the provision of some special means for carrying its weight, as for example where an existing building is being adapted to a new purpose or where the floors concerned are of timber. No real difficulty is presented, however, in the case of a new building, since the additional weight may be supported from the ground if necessary.

The effect of applying insulating material direct to the brickwork forming the flue is to reduce the rate of heat flow through the whole, and this necessarily reduces the temperature-difference through the brickwork itself, since the major drop of temperature will occur through the insulating material. Thus the surface of the brickwork against which the insulating material is secured is brought to a much higher level of temperature. Reference to Fig. 10 indicates the small temperature-difference through the high-conductivity brickwork as compared with the large temperature-difference which would result with the same thickness of brickwork when uninsulated and subject to the same overall difference of temperature between the fluids in contact with the faces.

This increase of temperature of the brickwork surface may have considerable effect both on the insulating material itself and on the materials used in securing it to the brickwork. The temperature at which combustion of the insulating material commences requires examination, and it is not unknown for fire to have broken out where this point has not been considered. If the insulating material incorporates an adhesive or binder which is liquefiable by the application of heat, the temperature of liquefaction is quite likely to be within the range obtained, and disintegration even of the inner surface alone would result in collapse of the whole. Bitumen becomes impossible as a fixing material on account of its fluidity at temperatures of 150° F. or lower. Timber plugs shrink and lose their hold, and the melting-point of white metal plugs may be low enough for them to be affected. Portland cement can only be applied at such times as the flue may be out of use, owing to the rapid dehydration caused by the hot surface, which robs the cement of water necessary to setting. Since some 24 hours are necessary for the final set of Portland cement, it is not possible to circumvent this difficulty simply by saturation of the brickwork before erection.

In the design of new buildings, it is usually possible to keep the hot surfaces of flues removed from low-temperature rooms. Sometimes it is unavoidable that a wall of a boiler house should abut on a cooled space, as for example in the constant-temperature cellars of licensed premises. The additional heat flow here is taken care of without difficulty simply by increasing the thermal resistance of the wall structure by means of insulating material. There is no complication due to the effect of high temperature on the materials themselves.

Before leaving this subject it will not be out of place to mention that it is possible for trouble to ensue through the reception of heat by solar radiation. Cases have been recorded of the collapse of cork slab insulation, erected with

hot bitumen, from the underside of a flat roof, even though the room below was in use as a cold store at a temperature around 32° F. Bitumen becomes progressively more plastic with increasing temperature, until plasticity merges into fluidity. A bitumen screed on the underside of a ceiling carrying a suspended weight of cork and plaster finish may become sufficiently ductile in the range 115°–150° F. for the cork to sink slowly and finally fracture the bond. A low melting-point of bitumen assists erection, but the extra trouble called for with bitumens of higher melting-point is worth the taking. Portland cement mortar remains unaffected by temperatures such as are produced by solar radiation, and while such material is available there is nothing in favour of using an adhesive which, although reasonably rigid at normal atmospheric temperatures, can only be described accurately as being a fluid.

Porosity.—The necessity of preventing interchange of the air enclosed in a constant-temperature room with the atmosphere involves consideration of the porosity of the materials it is proposed to employ. If the temperature is below normal atmospheric, the importance of porosity is enhanced because of the moisture contained in air and for which the air acts as a vehicle. Air which filters through a boundary of a refrigerated room is cooled in its progress, and under most usual circumstances will reach the dewpoint, with consequent deposition of moisture. The presence of moisture increases the conductivity, and further deposition is facilitated. Materials of high porosity are not suitable for insulated structures, particularly where the inside temperature is below freezing-point. Sooner or later the moisture will penetrate to the point where freezing occurs, and in time internal rupture of the insulating material will follow.

Some types of bricks are more porous than others, and as a whole bricks are more porous than normal concrete used in buildings. The quantity of water which they

absorb and the length of time during which air is released from them after immersion in water provide an indication of their porosity. Cracks in bricks allow much freer passage than does mere porosity of otherwise sound material, and for this reason heavy pressed bricks are more suitable than common wirecuts. Apart from their cost, blue bricks do not offer advantage, at least for the inner course, because of the reduced suction they afford to cement screeding. The contribution to thermal resistance made by the brickwork component of an insulated structure is relatively small, as has been seen (compare Fig. 10), and therefore an increase in conductivity of some 30 per cent. which may result when it becomes wetted does not affect the total thermal resistance to any serious degree. Continued absorption of moisture, however, will cause deterioration of the insulating material itself, if the rate of absorption is high enough for penetration of the wall to occur.

A test [6] at the National Physical Laboratory on 9-in. London Stocks set in cement mortar when saturated with water gave a Thermal Conductivity of $\mathbf{k} = 1{\cdot}8$ B.Th.U. per sq. ft. per hour per 1° F. After drying out for ten days this fell to 0·71, and after a further four days' drying, to 0·68.

The foregoing in reference to brick walls applies also to walls of stone and precast concrete blocks. The latter vary widely in composition, and the lighter variety of breeze concrete slabs are suitable only for internal work owing to their porosity. If used as external panelling in steel-framed buildings they should be protected from the weather, preferably by means of an independent surface. This may take the form of corrugated iron sheets secured to the steel framing, with an air space of about $\frac{3}{4}$ in. between the sheets and the slab wall. The alternative of waterproof rendering applied to the outer surface may fail in its purpose because of cracks caused by contraction of the rendering during ageing, or by transmitted vibration from roads, railways, etc.

Whereas in a dwelling-house the main value of cavity

walls from the thermal point of view lies in impeding heat flow outward during winter, in a building insulated for low temperatures the advantage lies in reducing the effect of solar radiation. It is not usual for a cavity to be incorporated, owing to the heavy loading of the walls in this type of building, and the addition of an extra leaf in order to obtain a cavity is not justified by the small increase of thermal resistance secured. A small increase in the thickness of insulating material is both less costly and more effective. Structural considerations may permit the use of a cavity in the panels of a framed building, and venting, which is a disadvantage in a dwelling-house, is more of an advantage in a low-temperature building.

Cavity Floors.—The introduction of hollow tiles in the construction of reinforced concrete floors in effect provided a very coarse aggregate of unusually low density, yet with adequate strength for the purpose intended. In addition a material contribution to thermal resistance was obtained by virtue of the air cushion enclosed within the tiles. Precast hollow concrete beams emerged subsequently, retaining lightness of construction and improved thermal resistance, and claiming as an advantage elimination of timber shuttering. Mass concrete has a high thermal conductivity which is derived mainly from the aggregate used, the conductivity of stone being amongst the highest possessed by building materials. For large buildings and/or heavy loading it is far from being displaced by more recent introductions. In common with cavity walls of brick or tile work, the increase of thermal resistance made possible by devices of this kind is small in comparison with that available from insulating material. It is certainly of value where amelioration of temperature conditions is sought, but is not considered seriously where constancy of temperature is required.

Adaptation of Existing Rooms.—The foregoing indicates the

trend which design would follow when unfettered by the necessity of acquiescence in structural detail which the cost of rebuilding might impose. Use can be made of many differing types of structures, provided that such amendment as may be necessary is a practical possibility. Existing walls of brick may possess a facing of plaster, tiling, or boarding. Or they may be painted or limewashed. Lime plaster is too frangible and has too weak a bond with brickwork for it to be considered as a base suitable to receive insulating material. Any endeavour to impart to it the necessary chasing which would provide a key for adhesive material used in the erection of insulating material is not likely to meet with success. The plaster cracks up into small sections, and the impact of a hand pick, instead of procuring a key, causes the bond which the plaster has had with the brickwork to be fractured. It is necessary to hack all the plaster from the wall, and at the same time to rake the joints of the brickwork, in order to ensure a proper key direct to the brickwork. Glazed tiling should be treated in the same way, since the weakest part is the bond between the tiles and the rendering—a bond which can be broken by a moderate impact—and the smooth glazed face offers no grip. Glazed, painted, or limewashed brickwork presents no security for cement mortar, although cork slab erected in hot bitumen as the adhesive material is sometimes successful against glazed brick. Blue brick is difficult because hacking of the surface is virtually impossible, and raking of the narrow joints alone must be relied on. The suitability of concrete walls cast *in situ* depends upon their age and the hardness of the aggregate used in the gauging. The best material and mix proves the most difficult to insulate, just as with brickwork the poorer and more porous bricks are the easiest. The increasing hardness of concrete as it ages increases the difficulty of securing a key. Bitumen is uncertain in its adherence to concrete, and both moisture and vibration may prove to be causes

of failure. This is especially noticeable on the underside of a suspended concrete floor, which is regarded as one of the most reluctant of building surfaces to accept even the light weight of insulating material.

Masonry walls of tooled stone which present a fair surface may be regarded in the same way as brick walls. Stone walls often are extremely irregular and present a difficult problem to straighten. This may necessitate filling with mortar as erection proceeds, with consequent slow progress, during which resort to propping may be necessary to prevent creeping of the fluid mix. If the walls also are not plumb, it may be desirable to erect a single-course brick wall against the stone in order to obtain a surface which is both true and plumb. Timber framework is a poor alternative which financial economy barely justifies.

Independent walls of timber framing are employed frequently to enclose a space in an existing building to be insulated as a cold store. Almost invariably the framing is covered on the outside with tongued-and-grooved boarding in order to present a clean and straight surface. If loose-packed insulating material is to be used, the inside of the framing is also boarded, and it is usual for the timber uprights to be of the same thickness as the insulation in order to carry both sets of boarding. This arrangement results in a proportion of the insulated surface, corresponding with the width of the uprights, being subject to a much higher rate of heat flow than the remainder of the area, and subject therefore to a more immediate likelihood of moisture precipitation. At this point, the contact of irregularly-shaped granules with the plane face of the timber upright leaves small passages through which air circulates more readily than through the main body of the insulating material, thus adding to the weakness of the already weak spots.

Instead of the timber framing extending from inside to outside face, it should be arranged in staggered formation,

each member of the framing carrying only one set of boarding and being no more than half the thickness of the insulation. All the framing is by this means covered by an equal thickness of insulating material, the rate of heat flow at these points is reduced, and the precipitation of moisture made more remote. The same principle is applied in connection with the use of material in slab form, the framework being limited to the thickness of one of the two or three layers of material and therefore being covered throughout by at least one layer of the material. Where a temperature below 20° F. is involved, the insulating material covering the framework (i.e. excluding that recessed between the various uprights and rails) should be erected in two layers in order to avoid small cavities penetrating the insulation, which absence of staggered joints of the slabbing makes possible.

The major advantage secured with the use of timber is structural rather than insulative, apart from lowness of first cost and speed of erection, in which it contrasts favourably with brickwork. In being capable of erection on ground or suspended floors without the necessity of foundations in the one case, or of coincident support in the other, it is a more facile material than those of high density which must be employed for the structure of buildings. Its use is circumscribed only by the load it is called upon to carry; and in being independent of the main structure, this loading is mainly that of independent ceilings. Reference to "ceiling" is made designedly and conveys that there is no intention, or in many cases no possibility, of using the upper side as a floor. The weight to be carried, then, is confined to that of the ceiling itself, invariably light from the use of timber, and rarely exceeding $\frac{1}{4}$ cwt. per square foot, with in some cases an additional load suspended below the ceiling. This suspended load may be partly standing load, such as that imposed by cooling coils and air ducts, and partly intermittent loading such as is imposed by the hanging of meat or other produce on rails.

If the rail is of the running variety in which the hooks are suspended from flanged wheels riding on the rails, there is an additional moving load. The latter is not great as a rule and rarely exceeds the 4 cwts. of a large side of beef, and so is within the capability of a timber ceiling. There is, however, some difficulty in coupling with it walls of timber, owing to the height—of about 14 ft.—at which the load must be carried in the case of full sides of beef.

A useful compromise in a case of this type can be effected by carrying the suspended load on steelwork, either supported on stanchions within the room, or housed in the main walls of the building, and relegating to the insulated structure its primary duty of " clothing " and isolating a region of temperature differing from that of the surroundings.

Penetration of the insulated boundaries, particularly by material of high conductivity such as steel, does not conform with the ideal of thermal insulation. It should not be considered where the room temperature is below the freezing-point of water. To take the instance in which compromise of this sort suggests itself most readily—that of a cold-room high enough for the hanging of sides of beef, with the problem of suspended load entailed—the duty of heat extraction is high in comparison with the insulation " loss," and the additional heat " loss " via the steel is not likely to be of great importance. The temperature required for chilling fresh-killed beef is some 3° F. above freezing-point, and trouble from condensation of moisture is the worst that is to be feared. It is most important to prevent creep of moisture along the steel, as this will find its way into the insulating material, with deleterious effect. The steel should be insulated for some distance inwards from the wall, on the same principle as ribbon insulation, and every care is necessary to secure complete airtightness of the adhesive material—preferably hot bitumen. The duty to be performed in the type of room instanced involves the forced circulation of a considerable volume of air. Fortunately,

this fact assists in reducing promiscuous condensation and concentrates it mainly on the surface of the cooling element. Favourable combination of circumstances may thus provide the justification for compromise in a departure from orthodox practice.

Penetration of insulation is, in fact, inevitable in a cold store, since the door-framing must contact with the air on each side and the rate of heat flow at this point is three or four times that through the insulating material. The delivery and return pipes carrying the refrigerant to and from the cooling element must pass through one or other of the boundary surfaces. The temperature of these pipes is always considerably lower than that of the room itself and so, in the majority of cases, is below the freezing-point of water. Increscent frost crystals find no difficulty in producing internal disruption of cement mortar, tiling, etc., and complete airtightness of the insulating material in contact with the pipes where they pass through the boundary is essential. It is usual for a timber framing to be fixed in the insulated structure through which these pipes are subsequently passed. The box so formed is then packed with loose insulating material which is retained by timber plates, secured to each side and halved on the centre line of the pipes.

This arrangement is barely adequate to exclude moisture-laden air and is much improved by the addition of cork pipe sections secured around the pipes in bitumen and extending 2 or 3 in. beyond the surface, both inside and outside. The pipe insulation which is usual outside the room is thus continued through the boundary unbroken. The timber end plates are then cut to fit the external diameter of the pipe sections and are protected from frost deposition by them. The protruding ends of the sections are covered with a bituminous compound. The remainder of the box is packed with loose material as before, but the airtightness of the whole is much improved. Great import-

ance should be attached to the symmetrical positioning of the pipes in the pipe box, as it is not possible for airtightness to be secured if one or other of the pipes is so badly fixed as to be in contact with the timber frame of the box, par-

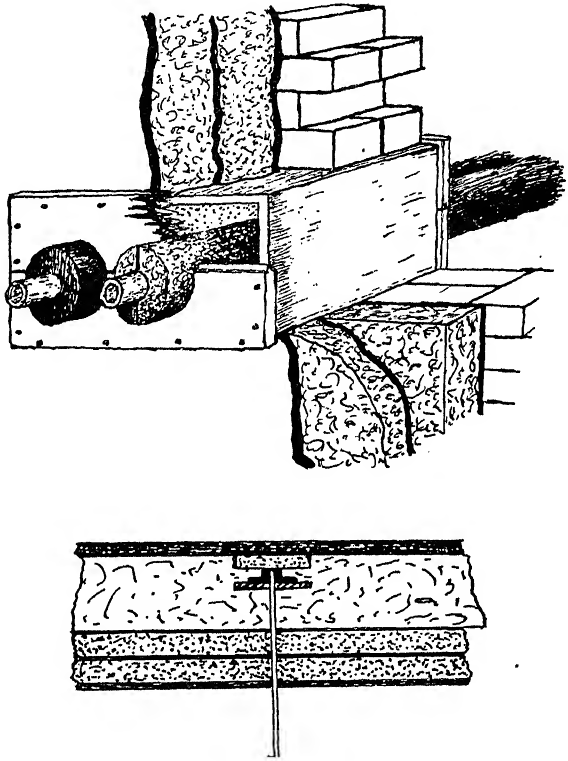


FIG. 19.—PENETRATION OF INSULATION

ticularly if it is in a corner. It is better for all pipes to be on one centre line, which may be either vertical or horizontal, and convergence or divergence of the pipes anywhere within the thickness of the boundary should not be permitted.

Penetration of Insulation by Hangers and Drains.—The necessity for suspending meat rails and, in some cases, cooling coils from the ceiling provides another instance of penetration which in practice is often unavoidable. The most favoured type of support is that of a coach screw buried in a timber joist, since there is no external contact with the steel. Hangers secured in concrete floors can be partially insulated only. When they are required for meat rails at a temperature above 32° F. this is not so important as when required for direct-expansion pipe grids at, say, 15° F. The split-end type of hanger is not manipulated as easily as the threaded-rod type with nut and plate, owing to greater difficulty of maintaining alignment. Further, it is possible with the latter type to interpose a thin block of hardwood, preferably teak, under the plate in order to break some of the direct contact with the concrete. The thickness of wood block possible is only about $\frac{5}{8}$ in. with the average thickness of concrete floor. It should be bedded level in cement mortar. Over the top of the plate, and recessed to take the nut if necessary, a piece of cork slab 1 in. thick and about 6 in. square may be placed. The upper side of this piece of cork generally comes level with the top of the concrete floor and is covered by the grano-concrete or asphalt topping without interruption of floor levels.

Gullies are necessary in cold rooms used for certain purposes, but are the better for their absence unless quite unavoidable. The necessity for trapping such outlets from rooms which should be airtight makes them unsuitable for use at temperatures below about 28° F., owing to the probability of their freezing solid and the subsequent difficulty of thawing them out without putting the room out of commission for a considerable period. Even if the floor does not require drainage, it is often necessary to provide for taking away the water when thawing off a cooler. In either case penetration of the insulation is inevitable. In the case of a ground floor laid directly on

earth, the conditions are not unfavourable owing to the natural protection of the earth. A drain pipe from an upper floor may produce condensation of moisture from the air, or "sweating" as it is termed. It should be remembered that if the room temperature is just below freezing-point, exposure of the drain to warmer air may serve to prevent freezing up, and that the application of insulation with the object of preventing "sweating" may do more harm than good. Drains which are small enough to be laid within the thickness of the floor insulation are protected adequately, but for larger gullies little can be done, since they must be firmly secured in the floor structure itself. This disadvantage is mitigated somewhat in that gullies are only necessary for purposes pursued in rooms of moderate, and never of low, temperature.

Lightweight Concretes.—Recently, developments in the field of structural concrete have taken place in the search for aggregates of low density which might provide an improved thermal resistance without too great a sacrifice of strength. Materials of greater density, broadly defined, possess greater structural strength than light materials, but also higher thermal conductivity. As a whole, the sphere of usefulness of each individual material is confined to the particular function which it is most suited to exercise, and coincidence of two opposing qualities cannot reasonably be anticipated.

No material known at present is capable of providing adequate thermal resistance for the purpose, say, of low-temperature storage, and at the same time of carrying load in compression commensurate with the weight of goods which such storage entails. Nevertheless, a use for lightweight concretes is found in the casing of steel stanchions, the filling of panels in framed buildings and generally where strong framework relieves the concrete of compressive load.

Attempts have been made to extend the use of these

concretes to the wall construction of small dwelling-houses in which breeze concrete slabs have long been used for internal partition work. The employment of lightweight concretes for the internal leaf of a cavity wall in which the outer leaf is of normal construction, is based on the sound principle of expecting from each material only the duty appropriate to its known qualities. Adherence to this principle in the design of constant-temperature buildings is of greater importance than in the case of dwelling-houses, where variation of temperature has no more serious effect than detracting from comfort.

Aggregates used in lightweight concretes include pumice, furnace clinker, foamed slag and expanded slate. The mix is lean in comparison with stone or gravel concrete, being variable from 1 : 6 to 1 : 10 and devoid of sand content. The density varies according to the mix, and the lower densities provide lower values of thermal conductivity.

TABLE XI.—LIGHTWEIGHT CONCRETES [4]

Aggregate	Density lbs. per cu. ft.	Conductivity B.Th.U
Pumice	41–48	1·1–1·4
Expanded Slate	55–68	1·7–2·1
Foamed Slag	69–80	1·7–2·2
Clinker	95–105	2·3–2·8

Concrete.—The word "concrete" is applied to a large number of different mixtures of which Portland cement is the primary ingredient. The aggregate may consist of stone, gravel or broken brick, in which cases sand is incorporated as a third constituent on account of the relatively large percentage of voids present. With fine and ungraded aggregates such as crushed granite, whinstone and coke breeze, the addition of sand becomes unnecessary. There are many variations possible in the volumetric proportions

of the various materials used in the mix, depending broadly on the coarseness of grading of the aggregate.

The thermal conductivity of stone concrete is high among building materials at about 7 B.Th.U., and is therefore about twenty-five times that of a good insulator. The conductivity depends mainly on that of the aggregate, which is present in a major proportion, and dense concrete incorporating stone provides the higher values. The greater the strength and resistance to abrasion of the concrete, the

Table XII.—Thermal Conductivity of Brickwork and Concretes

	Thermal Conductance C =	(Equivalent) Conductivity k = (B.Th.U.)	Ref.
Concrete			
Coke Breeze (to pass ½-in. sieve) 4, Portland cement 1	—	4·1	6
Granite (to pass ½-in. sieve) 4, Portland cement 1	—	5·1	6
Portland stone (to pass ½-in. sieve) 4, Sand 2, Cement 1	—	5·5	6
Ham River Gravel 2, Sand 1, Cement 1	—	6·7	4
„ „ „ 4, „ 2, „ 1	—	7·0	4
York Stone (to pass ½-in. sieve) 4, Sand 2, Cement 1	—	7·0	6
Brickwork			
London Stocks in Cement Mortar, 9 in.	0·68	6·12	6
Flettons „ „ „ 9 in.	0·70	6·3	6
Sand Lime „ „ „ 9 in.	1·03	9·27	6
Plasters			
Sirapite (neat)	—	3·1	6
Lime 1, Sand 2	—	3·3	6
Cement 1, Sand 4	—	3·7	6
Sirapite 1, Sand 2	—	4·5	6

greater is likely to be the conductivity. But the conductivity of all concretes, with the exception of those incorporating lightweight aggregates, is so high as to make the value of this material from an insulation point of view, in the thicknesses normally used in walls and floors of buildings, practically nil. The sum of the surface resistances constitutes approximately 70 per cent. of the total thermal resistance available from a 6-in. concrete slab, and an equivalent result is obtainable from a deal board only $\frac{5}{8}$ in. thick.

Adhesive Material.—The technique of erection of slabs of material such as cork includes two main variations in its application to walls. One method involves the use of cement mortar as the adhesive material, the slabs being covered and erected directly to the masonry wall. The small irregularities presented by all masonry surfaces are taken care of by the thickness of the screed applied. The alternative method employs hot bitumen or "asphalt" as the adhesive. The term "asphalt" does not imply a material corresponding with that used for surfacing roadways, but one consisting mainly of bitumen to which has been added sawdust or corkdust in order to give it body. The bitumen or asphalt is melted by heating and is applied in a fluid condition simply by dipping the slabs. The success of this method depends largely on the smoothness of the surface to which the slabs are erected, so that exclusion of air may be as complete as possible. In order to obtain a smooth surface, rendering of the wall with cement mortar is first carried out. Without this preparation the grip afforded by bitumen may be inadequate. It is in any case less than that afforded by cement mortar, which can be credited with a definite affinity for masonry not shared by bitumen. This will be obvious if cork slab is erected in hot bitumen to the underside of a concrete floor.

Under some circumstances, to place a non-porous screed in contact with porous material is not wise. As a rule it

is effective against moisture-laden air, but water leakage from a floor above, such as might occur in a dairy, may collect behind the non-porous screed and result finally in sudden fracture. If the screed were porous to some degree, visible evidence of the leak would be available for tracing and repairing the fault, and water pressure would not be set up owing to the release of the water through the porous material. Further, the soundness of a cement screed does not deteriorate when wetted.

The incorporation with the mortar of one of the many waterproofing mixtures of the stearine type is adequate to contend with slight dampness of walls. It should be remembered that the correct position for a damp-course is external to the main structure. If it is arranged between the insulating material and the brickwork, trouble is still possible if there is any pressure of water.

Compressive Loading of Cork Slab.—Light, compressible materials which make good insulators call for special measures when required to carry any considerable load in compression. Cork slab occupies an almost unique position in the matter of capacity for load-carrying. Highly compressed tiles made of virgin cork are capable of carrying loads of as much as 36 tons per sq. ft., according to results of tests made at the National Physical Laboratory. These tiles are about ½ in. thick only and are found to be permanently reduced in thickness after the release of the first application of the load. Subsequent applications of the same load again compress the tiles to the appropriate degree, when release of the load results in re-expansion to the reduced thickness, provided that the load is within the reasonable capacity of the tiles. But these cork tiles have a higher conductivity than the low-density, baked-cork slab used for thermal insulation, and even if the conductivity were low, the small thickness of ½ in. would not provide any large degree of insulation. They are useful for housing

the ends of beams, since only very small settlement under load is permissible in such positions.

Fig. 20 shows the percentage reduction in thickness of baked-cork slab occurring under load, and the progressive nature of this reduction indicates the difficulty of contending with any wide variation of loading. For this reason, distribution of the load over a generous area is essential, and the superimposed topping must be of adequate strength to prevent fracture if the loading may become at any time unequally distributed. This latter condition will occur frequently in the case of insulated floors of cold-storage warehouses, where the intermittent loading may vary from nothing to perhaps 3 cwts. per sq. ft.

The amount of compression of baked-cork slab is very small under any normal floor loading, and a topping of comparatively small thickness is adequate for a reduction in thickness of the cork which, at a loading of 3 cwts. per sq. ft., is only about $\frac{1}{32}$ inch in 6 inches. It is necessary however to make sure that even support is secured, and that the screeds of cement mortar in which the cork is laid are continuous and fair. The employment of multilayer insulation, with a view to staggering the joints of the slabs for thermal reasons, may result in the plane face of a slab which covers the joints between four contiguous slabs in the layer beneath riding on the high points of such of these slabs as may not be evenly bedded. Even though the first layer of slabs may not present a fair surface, it is still possible to correct the irregularities by suitable manipulation of the succeeding screed. For this reason, the screeds must be of adequate thickness; otherwise points may occur where the floor topping is in virtual suspension, and fracture may result. For this reason also, rough-surfaced concrete and floors in which falls have been formed in the base concrete in more than one direction, are not generally suitable for the use of hot bitumen as the screeding material, owing to the lack of body in this type of screed.

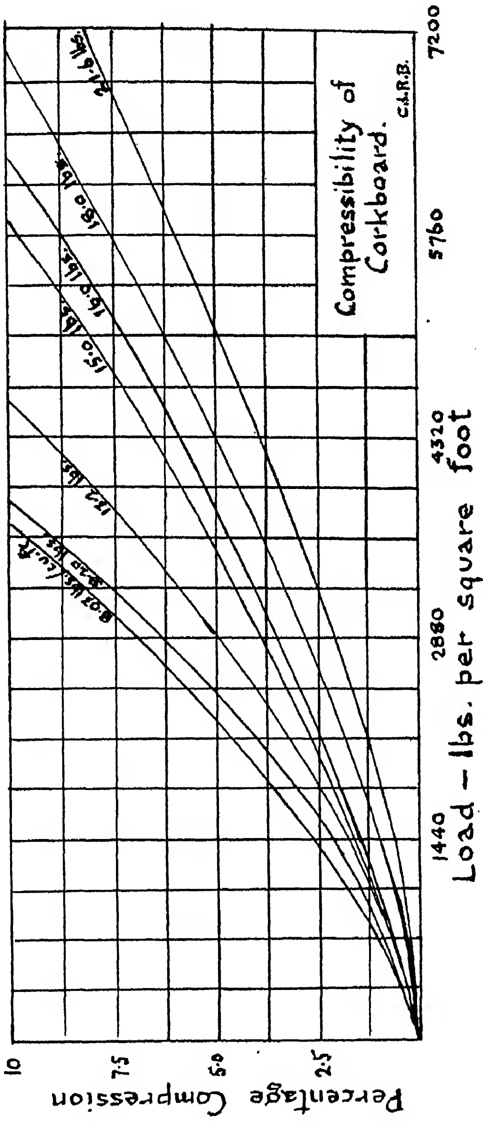

Compressibility of Corkboard.
C.L.R.B.
7200
5760
4320
2880
1440
Load – lbs. per square foot
10
7.5
5.0
2.5
Percentage Compression

FIG. 20.

It is quite possible for space for the deflection of slabs in a floor to occur to a degree far in excess of the deformation due to compression that is observable when the slab is evenly supported on a machine-planed surface. Provided the span of virtually unsupported topping is no greater than that which would be reasonable if the topping were elevated on raised screeds and so became a suspended floor, no actual harm accrues, but shock load may discover weak spots.

The usual form of shock load is produced by the accidental falling of a heavy case. Trucking produces temporary concentrated load at the areas of contact of the wheels with the floor. Where the service is to be heavy, steel reinforcement of the topping is desirable. If the heavy service is more in the nature of an abrasive action than that of load-carrying, surface reinforcement of cast iron or steel, or the incorporation of a ferrous aggregate, will be preferable. Such a condition occurs at the thresholds of doorways, where the traffic load is heaviest.

A heavy topping has the advantage of taking up any initial deflection of the slabs which may be necessary to produce full distribution of the loading. Where a heavy item such as a compressor is to be carried on cork slab, it is usual to isolate the machine-bed from the remainder of the floor by placing the slabs on the vertical surfaces of the machine foundation as well as on the underside—the whole being sunk below floor level. This arrangement permits the inevitable compression of the base cork to occur without straining the unloaded topping immediately surrounding the foundation. Alternatively, if it is more convenient for the cork slabs to remain on one level, as in the case of upper floors, the additional thickness of concrete forming the foundation may be built up above floor level. In this case, the area of heavy loading may either be isolated as before or may be increased by distribution of the load over a wider area. The latter requires a gradual reduction in thickness

of the concrete in order to avoid the sudden change of stress which would result from stepping down sharply.

An example of a particular form of loading of cork slab is found in the case of brick (glazed or otherwise) lining to the walls of a cold store. Single-course brickwork (stretcher bond) is employed, and a height of 7 ft. imposes a load on the floor of some 8 cwts. per sq. ft. The compression of 4-in.-thick cork under this load is about $\frac{1}{16}$ in. and may be provided for in the following manner. A concrete foundation one brick in width and from 4 in. to 6 in. in height, according to the height of the skirting desired, is first laid around the walls. With it is cast a strip of floor 3 or 4 in. wide and of the appropriate thickness, and then the coving is completed. This device provides a foundation of an area some 60 per cent. greater than that of the brickwork and so reduces the amount of deformation of the cork. Also, it takes care of any places where the support offered by the cork is, for any reason, less than it is elsewhere. The brickwork is then laid in cement mortar in the usual manner, and only after the whole load of brickwork has been taken by the cork is the main area of floor topping laid. Bitumen expansion joints may be employed between the main area of topping and the concrete wall foundation if desired, but this is only necessary with large floor areas and heavy intermittent loading of the floor.

Asphalt topping over cork slabs is in general use in brewery applications where waterproofness is essential. The plastic nature of asphalt makes it suitable for standing loads of less than half the moving load which is within its reasonable capacity. Depending on the mix, the latter is in the region of 2 tons per sq. ft. Heavy tanks containing 2,000 or more gallons of liquid create a loading often exceeding this figure and, as they are stationary, it is not possible to carry the supporting feet or cradles directly on the asphalt without some more rigid support. Not only is the compressibility of cork slab about 15 per cent. in thickness at

2 tons per sq. ft., but the ductility of asphalt would cause still further depression, creating pooling of water and inability of the floor to drain. In time, fracture of the asphalt would result.

There are two methods of preventing trouble from this cause. Firstly, the provision of a concrete topping over the whole floor area, of a thickness adequate to distribute the point loads without fracture. A thickness of 4 in. with fabric reinforcement is sufficient in most cases. The asphalt is laid on top of the concrete and carried up the tank feet to a height of 6 to 9 in.

The alternative method involves the use of hardwood blocks inlaid in the cork at each point of loading, for the purpose of avoiding the depression which would result in the cork. In order to combat the depression of the asphalt, which would still occur and be measurable even in a thickness as small as $1\frac{1}{2}$ in., the hardwood blocks should be of a thickness equal to that of the cork slabs plus that of the asphalt topping. The asphalt is carried over the timber blocks and thus is raised a little above the general floor level. Then, however much depression may occur in the asphalt, pooling will not result. The total variation in weight of the tank when empty and when full may be in the region of 10 tons, or some 2 tons per sq. ft., and the variation in linear compression of cork slab under such loading would be considerable if it were called upon to carry the weight direct.

Insulated brine and water tanks should be carried directly on cork slab, and the provision of timbers between which the cork is laid with the object of taking the weight of the tank is a mistake. With loose-packed insulating material, timbers must be used, but with cork slab they merely defeat distribution of the load. Further, with ordinary manufacturing methods it is practically impossible to obtain equality of loading of timbers. The resilience of cork slab takes care of small irregularities in the tank surface, including

rivet heads, without the necessity of special levels or incisions.

Uninsulated tanks standing on an insulated floor cause a compressive load on that part of the floor insulation which they cover. The amount of compression is of importance on account of deflection of the floor topping and the possibility of consequent cracking, and here suitable distribution of the load must be secured by means of timbers, brickwork or concrete foundations.

The Crazing of Portland Cement Plaster.—The appearance in finished plaster surfaces of fine cracks, or " crazes " as they are called, is often a source of disappointment to purchaser and insulator alike. Crazing of cement-mortar renderings occurs more readily on a slab-cork foundation than on brickwork. A sample of neat Portland cement kept under water exhibits continuous expansion, but when kept in air it contracts to a still greater extent. If cement be mixed with sand in the proportions 1 : 3 the effect is greatly moderated and only slight contraction is evident, whether the sample is kept in water or in air, being greater in air. According to *The Making and Testing of Portland Cement and Concrete* (G. & T. Earle, Ltd.), page 32, the degree of contraction of a 3 : 1 sand-mortar sample as tested by the Bauschinger Apparatus is 0·03 per cent. at the end of one month, when kept in air; this increases to 0·035 per cent. after 3 months and to 0·04 after 6 months. Expressed otherwise, the amount of contraction is $\frac{1}{32}$ in. in 8 ft. 8 in., 7 ft. 5 in. and 6 ft. 6 in. respectively. A craze is rarely more than $\frac{1}{64}$ in. in width, and therefore if the rendering is free to contract without resistance, crazing might be expected, even in comparatively small areas. A rigid foundation of brickwork offers considerable support to renderings, but a light resilient material such as cork slab offers but little resistance to the forces involved.

These forces are of considerable magnitude, since the

tensile strength of 3 : 1 sand mortar between 7 and 28 days of age is in the region 300–400 lbs. per sq. in. Thus, rupture in the continuity of the plaster occurs. This is of little importance from the point of view of strength, but might be a disadvantage where the porosity of the building material is high. Crazing has been known to extend several feet across the face of white glazed tiles, taking the line of released stress in the rendering behind, rather than following the path of lesser resistance offered by the perimeter of the tile units. If the craze is visibly open to the naked eye, say $\frac{1}{64}$ in., it may be found, on removing some of the rendering, that the cork itself has been crazed by the contraction of the plaster.

The release of this stress is facilitated by vibration, such as is set up by the slamming of a door or the impact of a hammer on a chisel or nail. Transmitted vibration from rail or road traffic and, in the case of timber ceilings, small variation of deflection under intermittent loading (e.g. meat rails) are other contributory causes. For this reason the size of joists forming an independent ceiling should be greater than that indicated merely by their capacity to carry the particular load, in order that deflection may be practically eliminated.

Cement renderings expand when wetted and contract again as they dry out once more. In common with most other materials, they expand and contract with temperature rise and fall respectively. The insulation of a cold room is carried out at normal atmospheric temperatures, whereas the artificially produced temperature to which the renderings are finally subjected may be more than 50° F. lower than this. The amount of contraction resulting from a reduction in temperature of 50° is approximately the same as that which takes place in one month due to the inherent tendency of this material, and this enhances the inclination to craze. Increase of the cement ratio increases the amount of contraction, while decrease beyond 1 : 3 is not to be

recommended, as the percentage of voids in sands suitable for rendering is fairly consistent at about 30–32.

It must be accepted therefore that Portland cement renderings on cork slab are likely to craze, and that there is a limit to the area which will withstand the stress involved without fracture. The limiting area varies with several factors and cannot be determined with exactitude. Fine sand is not as suitable for admixture with cement as a coarser sand, and soft loamy sand should be rejected in favour of a sharp sand. Sand which is so sharp that it becomes difficult to place is not suitable for renderings, and is more aptly described as grit sand, suitable for concreting.

The large superficial area of plaster renderings, relative to the weight of mortar, tends to result in uneven drying. In order to counteract this, cement renderings should be wetted thoroughly as soon as setting is complete. This occurs normally about 24–36 hours after placing. If wetting down can be continued for several days, during which the rendering is gaining strength, so much the better. Evenness of curing is assisted by the use of a fine spray rather than a jet of water. Plaster which rapidly turns light in colour is drying too quickly, probably owing to a local draught, and is more likely to craze than plaster which takes some 5 to 7 days to lighten appreciably.

An even thickness of rendering is obviously desirable. Unfortunately this cannot be retained, owing to the necessity for scratching the first coat in order to provide a key for the second. Symmetrical and unidirectional combing, however, may assist in preventing the aimlessness of direction of crazing which is so often evident. It is useless to resort to light and occasional surface scratching, which may not provide an adequate key for the second coat, particularly if the final coat consists of a gypsum plaster such as Keene's or Parian. These plasters do not contract initially to the same degree as cement renderings, and if the service temperature is considerably removed from that at which

application is carried out, a further straining of the security is set up.

Unless a definite suspension of work is authorized, the second coat of plaster will follow the first too soon, except in large rooms. In many cases, wetting down is either of a cursory nature or is not possible at all, since some 48 hours' drying is necessary immediately preceding the application of the second coat. Renderings of this type are not called upon to evince strength comparable with that of load-carrying structures, and a successful method of avoiding crazing takes advantage of a difference of age between the first and second coats. The rate of contraction inherent in cement mortar is greatest in the first few days of its life, and becomes progressively less as time goes on. At the same time the mortar is acquiring strength. If therefore the first coat of rendering is allowed to strengthen, contract, and if it will, craze, during a period of days before the second coat is applied, these processes will be, and remain, so much ahead of the same processes in the second coat. The full potential contraction of the second coat is resisted by the already strengthening first coat. In order to assist contraction of the first coat this should be divided off into panels. It is rare for crazing to occur in panels of 50 sq. ft., say 7 ft. by 7 ft., or 6 ft. by 8 ft., which dimensions accommodate themselves to the majority of cold rooms. In high rooms it is advisable to divide the walls horizontally, and the major dimension of a panel should not exceed 8 ft. The junctions of ceiling panels should always coincide with those of the walls, as otherwise the opening of the joint which occurs may induce a craze in the panel abutting the joint. Similarly the sides and soffits of beams should be divided in continuity with the ceiling divisions. This has the added advantage of symmetry of appearance.

If the second coat is to be a gypsum plaster it is applied continuously in the usual way. A finishing coat of cement mortar, however, should preferably be panelled also, in

which case the junctions of the panels should be Vee-ed and should coincide exactly with those of the first coat. It is usual for the apex of the Vee to open, but in this position it is not unsightly and can be filled after about 8–10 weeks, if considered desirable. In practice, the width of opening of the Vee is often greater than that which would have occurred in promiscuous crazing of unpanelled surfaces, and indicates the more complete release of internal stress secured by panelling. Few will consider the visible joints of panels to be inartistic, provided adherence to strict symmetry is maintained, and with this in view the positions of the panel junctions should be set out accurately.

Crazing of cement renderings on cork slab occurs mainly between one and eight weeks after application. Delay in the completion of erection is not looked upon with favour in these days, and, striking a balance between conflicting requirements, a period of ten days between first and second coats appears reasonable. Even this is often difficult to arrange in small rooms, where the total time required for plastering may be no more than four or five days. For the first eight days, wetting down should be practised.

Settlement of new buildings is a cause of crazing against which little can be done. Crazing may be promiscuous in spite of panelling, but is likely to be less extensive in character. Reinforcement of cement renderings with wire netting of 1-in. mesh is valuable in resisting crazing.

Cracking of Grano-Concrete Floor Toppings.—The maximum size of floor panel which is reasonable to adopt is generally that which is determined by convenience of laying. This is likely to be not much more than 10 ft. in each direction. It is preferable to anticipate a probable opening of panel joints by making them of definite width (say $\frac{1}{4}$ in.) when laying, and filling the joints after 7 days or more with a compound of emulsified bitumen.

The greater thickness of grano-concrete topping as com-

pared with wall and ceiling renderings, and the more favourable position for maintaining a wet condition, are sufficient to obviate promiscuous crazing, but it is not unusual for ordinary butt joints to open slightly in medium and large areas. Steel reinforcement may be considered for large areas, but it is not likely to be more successful for this particular purpose than an expansion joint, particularly where the room temperature is a long way below atmospheric temperature.

New Concrete Laid on Shuttering.—Where new concrete roofs are to be laid, it is advantageous to lay slab insulating material, such as cork slab or insulating board, on the temporary shuttering prior to the concrete being poured. This has several advantages. Firstly, it avoids the tiresome and more expensive hacking of the soffit after the shuttering has been struck, since a sufficient key is essential in order to carry the weight of the insulating material and the still heavier plaster finish which is customary. Some 12 days with Portland cement, or 5 days with rapid-hardening cement, are necessary for ageing of the concrete before it has attained sufficient strength to justify removal of the temporary shuttering. The increase of strength during this period involves also an increased difficulty in picking to form a key, and temporary support of the slabs during the setting time of the mortar used for erection is necessary. This is effected preferably by means of propping with timbers for a minimum of 48 hours. Even so, the bond of the slabs with the concrete is never as secure as that obtained by the method of pouring the concrete on to the insulating material, which previously has been laid with tightly butted joints on the shuttering. The careful butting of all joints is essential in order to prevent the finer elements of the concrete running through and breaking the continuity of the insulation. Also, it is then not so essential to butt tightly the joints of the timber boards, and gaps up to ½ in. are no disadvantage.

The cement and fine aggregate run into the interstices of the insulating slabs and form a bond. Since the weight of a 6-in. thickness of mass concrete is about 75 lbs. per sq. ft., the bond with the insulating slabs is made under continuous pressure and becomes capable of carrying a considerable suspended load. Alternative devices to assist erection of insulating slabs to the soffit of existing concrete roof slabs have but little to recommend them. They include the in-casting of timber blocks in order that nailing of the slabs can be practised, with the object of providing the temporary support during the setting period of the cement mortar. The nails are not withdrawn subsequently owing to the difficulty and expense of doing so. The timber blocks, which are about 4 in. square by 2 in. thick, detract from the strength of the concrete roof owing to their number. This may reach one per each $1\frac{1}{2}$ sq. ft. of roof area, where slabs of 3 sq. ft. are employed.

Another method involves the use of bolts or hoop iron, in-cast with the concrete, to which timber battens are secured subsequently. This is somewhat troublesome, owing to the careful positioning necessary and the possibility of displacement by the weight of the concrete when pouring. In addition, obstruction to striking of the shuttering is caused.

Secondary rolled-steel joists in mass-concrete floors should be arranged clear of the insulating slabs by $\frac{3}{4}$ in. or more, in order that the concrete may find its way under the lower flanges without difficulty. The slump value of concrete giving high strength is low, and the ratio of gauging water to cement is less than that desired by the average builder on the score of workability. A stiff mix can be used for pouring on insulating slabs, and of course is to be recommended on account of strength. But in order to ensure at the same time sufficient flow of the finer elements of the concrete to fill the interstices of the slabs and so obtain a proper hold, it is necessary to resort to a thin skimming

of cement mortar. This is laid on the slabs at the time the concrete is poured, and by this means the advantage of the dry mix is retained without danger. A good stone ballast passing a screen not greater than $\frac{3}{4}$ in. and down to $\frac{1}{4}$ in. is suitable.

Before using any admixture to the concrete mix for hastening the setting or other purposes, it is important to ascertain whether the material proposed has any effect on the particular insulating slab. Alkalis, e.g. sodium carbonate (washing soda), extract a deep brown stain from baked-cork slab, and the cork in immediate contact with concrete containing this substance powders slowly. This results in eventual collapse of the remainder. Sodium carbonate is used occasionally as an admixture by uninformed builders in order to accelerate setting of concrete. Its use in concrete for ordinary purposes is not recommended, but if brought into contact with cork slab trouble is certain. Even where used as a cleaning agent on floors subject to accumulation of grease, it may cause damage to cork slab on the underside by percolation through a floor slab which is not entirely non-porous.

Hollow-Tile Concrete Floors.—Reinforced concrete floors in which rows of hollow tiles are connected by ribs of concrete containing steel rods as the tension members, do not present an area of concrete on the underside adequate to carry insulating slabs, since the width of the tiles is frequently four times that of the ribs. The tiles are normally laid dry on timber shuttering, but when it is desired to cast cork slabs and floor in one operation the tiles should be set down on the cork in cement mortar. The screed need not be any thicker than that necessary just to cover the cork and fill the keyways of the tiles. Too thick a screed is likely to result in some of the tiles becoming displaced in level.

Precast Hollow Concrete Beams.—These should possess a

Table XIII.—Recommended Thickness of Insulating Material for Use in Cold Stores

(The thicknesses given are for Cork Slab. For Granulated Cork or Slag Wool, increase the thickness given by 33 per cent., reckoning fractions of an inch as one inch—see p. 100.)

Air Temp. of Building ° F.	Abutting Earth		Exposed to Air at 75° F.	Exposed to Solar Radiation Latitude 51° N.		
	A	B	C	D	E	F
53	–	–	2	3	4	5
44	–	2	3	4	5	6
35	2	3	4	5	6	7
27	3	4	5	6	6–7	8
18	4	5	6	7	7	8
8	5	6	7	8	8	9
– 2	6	7	8	8	9	10
– 11	7	8	9	9	10	10*
– 21	8	9	10	10	10	10*
	Basement floors.	*Basement walls.*	*Walls.*	*Unshaded walls.*	*Flat roofs flooded with water.*	*Flat roofs not flooded.*
	Not less than 5 ft. below ground level: Concrete, Brick or Stone—any thickness.	Brick, Stone or Concrete—any thickness.	Brick up to 14 in. Concrete up to 18 in. Stone up to 24 in. Boarding.	Brick, Stone or Concrete—up to 16 in.; then as in Col. C.	Mass concrete. Hollow tile. Precast concrete beams. Boarded joists. (All topped with asphalt.)	Mass concrete. Hollow tile. Precast concrete beams. Boarded joists. (All topped with asphalt.)
		Ground floors. Concrete, Brick or Stone—any thickness.	*Suspended floors and soffits of ditto.* Mass concrete. Hollow tile. Precast concrete beams. Boarded joists. Brick arch.	*Ceilings forming attic space to pitched roofs.* Mass concrete. Hollow tile. Precast concrete beams. Boarded joists.		
	For small rooms placed in basements mainly devoted to other purposes, use Column C.					* Flooding desirable.

Note: Symmetry of design would suggest that the maximum rate of heat flow should be the same on all the bounding surfaces. But to arrange this for the surfaces under columns E and F would involve considerable expense in comparison with columns B and C, which represent a rate of heat flow in the region of 2·00–2·25 B.Th.U. per sq. ft. per hour. Accordingly the thicknesses in column E represent a value of q = 2·66 approximately; and those in column F, values of q between 3·2 and 4 (the higher figure applying to the highest room temperature). In any case, integral thicknesses of material do not permit exact equality of heat flow.

hatched soffit provided in the mould. Since the *raison d'être* of beams of this type is the avoidance of the necessity of shuttering, it is necessary to erect the slabs to the soffit of the completed floor. A useful alternative to propping of the slabs during setting of the cement mortar is made available by separating the beams by about an inch and filling the gap with a tapered timber batten, flush with the bottom of the beams. The slabs are nailed to these battens instead of being propped. The separation of the beams permits the housing of steel hangers for rails or pipe grids with ease. With unseparated beams, considerable difficulty presents itself.

CHAPTER V

DOMESTIC BUILDINGS

The application of thermal insulation to dwelling-houses and other buildings has not yet received the attention which it merits. Not only has knowledge on the subject become more readily available, but suitable materials of various types are in regular production on a comparatively large scale. Furthermore, insulation has gained in importance, rather paradoxically, with recent improvements in building methods and materials, for the increase in the load-carrying capacity of modern structures has brought with it a general increase in rate of heat loss. The country cottage of some three centuries ago, with thatched roof and timber-framed walls filled with clay and straw, possessed a marked superiority over the modern type of dwelling-house from the point of view of thermal resistance. The hollow structure of straw and the considerable thickness of thatching, which it was necessary to employ in order to ensure weather-proofness, combined to provide an efficiency of insulation much higher than that obtained from material of high conductivity and small thickness such as tiles and slates. The cellars of modern licensed premises—palatial edifices of good brick set in cement mortar—compare favourably with those of the old roadside inn when viewed as buildings, but unfavourably as regards the maintenance of the equable temperature conditions which cellarage demands.

The thermal resistance offered by the usual 9-in. brick wall faced with lime plaster, which is so tolerantly accepted for house construction, is quite inferior in comparison with the efficiency of insulation considered indispensable to

industrial process. The incorporation of a cavity in the construction of brick walls has the effect of raising the resistance from about 3·7 (9 in. thick) to about 4·5 (11 in. thick), although cavity walls were not introduced solely for thermal reasons but primarily for the localization of moisture absorption. This improvement reduces the heat flow from 9·45 to 7·7 B.Th.U. per sq. ft. per hour in the depth of winter in this country, under a temperature-difference between the interior and the atmosphere of 35° F., but this figure is more than twice that acceptable for low-temperature rooms. This high rate of heat flow is not reflected convincingly in heavier bills for fuel, simply because no criterion is to hand which would provide the necessary evidence. The fuel bill is accepted as being normal and inevitable, whereas the reduction in cost which would become available from the use of insulating material, and the comparatively short period in which the additional expense of such material would be paid off, never emerge for consideration. The tolerance extended by the average householder towards a scheme of thermal inefficiency in which marked improvement is possible, would be shaken if note were made of the rapid rate of fall of temperature when the fire burns out, and if consideration were given to the B.Th.U. figure available in the fuel before combustion and to the various channels contributing to its final dispersal.

The amelioration of temperature conditions in a dwelling-house is similar in most respects to the problem of maintaining constancy of temperature for the purposes of some industrial process. There is one major point of difference, in that airtightness of dwelling-rooms is not desirable and actually, with the open type of fire, impossible. Some means of ventilation is necessary to the respiration of persons, and oxygen is necessary for combustion of fuel. Control of ventilation, however, is an important factor, since in buildings of this type air filtration is somewhat haphazard.

Air Circulation and Filtration.—The heat contained in a room is held by articles of furniture and other interior objects, and is received by them mainly by radiation. The heat capacity of the enclosed air is not great, and as in many cases direct interchange of air occurs, the temperature falls rapidly as soon as the source of heat is discontinued. The cool air, on entering, receives heat from the furniture, and in a comparatively short space of time the heating effect is lost, partly through heat being conveyed to the boundaries and being lost to the atmosphere, and partly through direct loss of warm air and replacement with cold. Lime mortars and plasters are porous to air, and air interchange is aggravated by wind pressure. Wall-paper is of some assistance in countering the porosity of plaster, but uncovered cracks, more particularly in ceilings (owing to the tendency of warm air to rise), are of more importance than porosity of the surface as a whole. Ill-fitting windows in their frames, or window-frames in the brickwork, admit a considerable quantity of cold air, and in circulating in the room the air acts as a vehicle for the transfer of heat from warm objects to the boundaries. The relatively low thermal resistance of the latter—particularly the single thickness of glass in window lights and the single thickness of plaster on bedroom ceilings—is largely responsible for the rapid fall of temperature which is usually experienced. It is advisable and usual for ventilating bricks to be built into the walls of dwelling-houses, in order to admit air to the under-side of the timber joists and boards forming the ground floor. This is very necessary for the prevention of mould growths and the ruination of the timber by dry rot, since dampness provides the conditions most favourable to the growth of the lower fungi. Unfortunately this arrangement causes a circulation of cold air which makes contact with the floor and increases the loss of heat through this boundary. The usual method of countering this loss is by the use of carpets, but even this results in a high rate of heat flow, as the

effective thickness of carpet may not exceed $\frac{3}{8}$ in., and the entire area of the floor is not always covered.

Holes left in the walls through which are passed waste and overflow pipes are frequently not made properly air-tight, and considerable air filtration may occur at these points—the precise places where much trouble can be caused through freezing-up. In addition, access for the air to the cavity of a wall of this type may be provided at the several points of penetration by the pipes, and this enhances the effect of porosity of the outer leaf of single-course brickwork.

Cavity Walls.—A cavity of some 2 in. width provides comparative freedom for the circulation of air, especially if orientated vertically. Brief consideration will show that if such a cavity is vented to the extent of permitting free circulation of atmospheric air, the effect is to surrender the thermal resistance of the outer leaf of the wall, and therefore the total resistance of the wall will be actually less than that of a similar thickness of brickwork in which no cavity is incorporated.

The possibility of filling the cavity with suitable material suggests itself as an alternative to a vacant cavity. It is important to note that, if such a device is to be successful, the conductivity of the filling material must be sufficiently low for a thickness of 2 in. (or whatever it may be) to offer a thermal resistance greater than that offered by the surfaces of the vacant cavity. The equivalent conductivity of a cavity of this thickness is about 1·2 B.Th.U. at a mean temperature of 45° F., and therefore an equivalent effect is obtained by filling the cavity (2 in.) with material of conductivity 2·4. Concrete, sand and earth all give a conductivity in excess of this figure, and from a practical standpoint this means that only materials which can be truly described as "insulating" are worth employment.

A difficulty is likely to arise in the application of this idea, viz. in the exclusion of moisture from the insulating material.

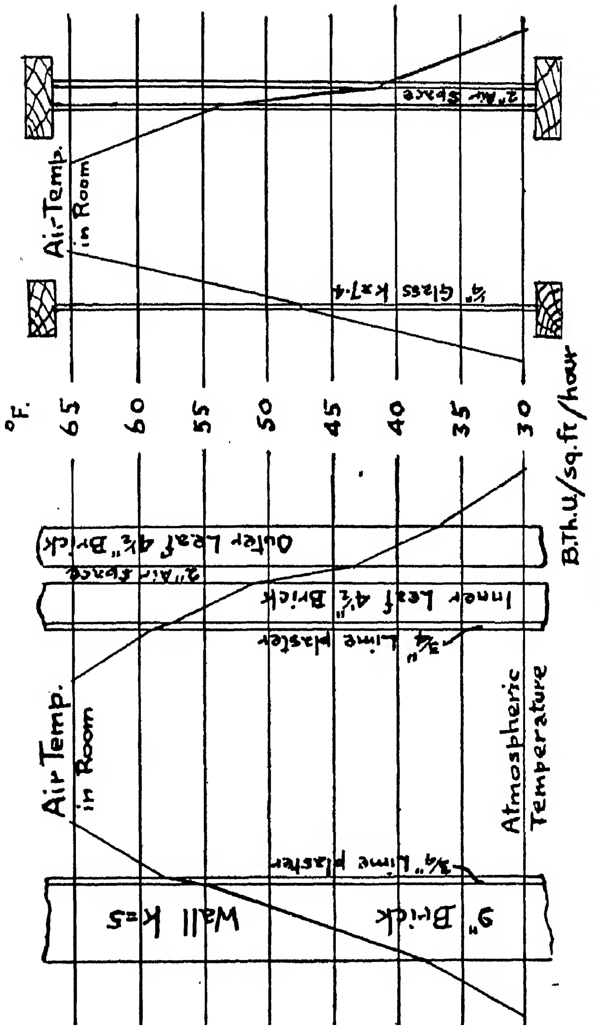


FIG. 21.—THERMAL ADVANTAGE OF CAVITY WALLS AND OF DOUBLE GLAZING

The original conception of the cavity type of wall regarded the outer leaf as being isolated from the inner, and therefore free to receive and reject moisture without transmitting it to the inner leaf. Bridging the cavity by filling is likely to defeat this purpose; and moreover absorption of moisture by the insulating material increases the conductivity very considerably. It then becomes necessary for the outer leaf to possess a lower degree of porosity than results from the adoption of ordinary bricks and lime mortar. With this in view, the type of brick it is proposed to use requires careful selection, and Portland cement mortar should be specified throughout, instead of merely for the pointing. A refinement may be added by incorporating in the mortar mix one of the many waterproofing compounds which are now available for use with Portland cement. It is possible for insulating material in slab form to be used by erecting it with waterproofed mortar as the building of the outer leaf proceeds. On the other hand, if the cost of material such as slab cork is agreeable, it would seem preferable to erect the insulating material against the inner surface of the inner leaf and thereby leave to the cavity its primary function of confining moisture absorption to the outer leaf. With this arrangement, the thermal resistance of the insulating material is supplemented by that of the cavity.

Wall Insulation.—In general, the erection of insulation to the interior surface proves the most convenient method of increasing the thermal resistance of walls. This plan obviates uncertainty of result due to variation in porosity of the materials used in building, and is rather simpler to apply. Slab cork $1\frac{1}{2}$ in. thick may be erected in cement mortar directly against the brickwork and subsequently plastered. The resulting thermal resistance is approximately twice that of an uninsulated 9-in. wall. Alternatively, and at rather less cost, insulating board manufactured from wood pulp or cane fibre may be used. The usual thickness is $\frac{1}{2}$ in.

and it is erected against timber battens of 2 in. × 1 in. secured to the brickwork by plugging. The centres of the battens are recommended not to exceed 16 in. apart, and the spaces between the battens form cavities which contribute to the thermal resistance. The increase of resistance over that of an uninsulated 9-in. wall is about 22 per cent.

It was shown in Chapter III (page 87) that the time required for a given change of temperature-difference varies directly as the thermal resistance, assuming that all loss of heat occurs only by flow through the boundaries. Not only does the employment of insulating material reduce the rate of temperature fall each time the source of heat supply is discontinued, but in addition the heat loss per hour during the continuance of heat supply is diminished, with resulting economy of fuel. The necessity of preventing promiscuous filtration of air must be emphasized, because the provision of insulating material is rendered nugatory if the thermal resistance which it affords can be circumvented by the circulation of air. For this reason, double glazing of window lights has been adopted in countries where extremes of temperature call for special measures.

Window Lights.—The rate of heat flow through glazed windows is almost halved by double glazing, in addition to the great improvement in airtightness which is obtained. The inner pane should not be a fixture but carried in a hinged frame to permit of cleaning. The distance between the panes should not be less than 1 in., as the rate of heat flow tends to increase with reduction in width of the cavity beyond this point. On the other hand, nothing is to be gained by widening the cavity unduly, and the minimum distance which will accommodate the framing is preferable to a wide cavity. Assuming airtightness of the cavity and still atmospheric conditions, the rate of heat flow through a double-glazed window at 35° F. temperature-difference is

about 13·7 B.Th.U. per sq. ft. per hour, which compares with 23·5 B.Th.U. for single glazing.

Fixture of the inner panel of glass would be a mistake for a second reason other than that of cleaning, since it would preclude fullest possible advantage being taken of solar radiation as a warming agent.

The high rate of heat loss through single glazing suggests the advisability of providing a removable cover for the whole window light, in order to increase the low thermal resistance during the long hours of darkness in winter. Heavy curtains are of little use unless non-porous and secured on all edges so as to make them reasonably airtight. Some people will be content with the appearance of warmth which such curtains provide. Until the end of last century it was usual for close-fitting folding shutters to be arranged for covering window lights, and these were made of several stout timber panels suitably articulated. The origin of shutters lay, no doubt, in giving a measure of defence after nightfall, and in addition they served the purpose of a blind or curtain. But they also made a real contribution to the reduction of heat loss, and the disappearance of such devices from modern house design can only appear progressive to those who attach little importance to thermal equability. Double glazing represents, however, a real improvement.

Internal ventilators at the ceiling line, which were desirable when windows were shuttered, have also disappeared. It has become customary, however, for rooms which have no fireplace, and lack the natural ventilation afforded by a chimney, to be provided instead with a grid type ventilator direct to the atmosphere. Such an arrangement of direct air interchange does not assist temperature control. Slight warming of the air in the room causes it to rise at once to the ventilator, where it promptly escapes and is replaced by cooler air from floor level. The air temperature in the room as a whole hardly rises, and direct radiation, such as

from an electric fire, will warm only such areas as are subject to impingement of the rays. Central heating mitigates this disadvantage to some extent.

Resort is made to multiple glazing in the design of refrigerated display counters, but with fixed panes and usually three panes forming a double cavity. Owing to the difficulty of securing airtightness of these cavities, and with the object of coping with the ensuing condensation which will occur, it is usual for vents to be provided at the top and bottom of the cavities, together with some means of dehydration. This consists in a tray containing a hygroscopic salt such as calcium chloride. The venting of the cavities, however, sacrifices much of the thermal resistance, and the cure is also an aggravation of the disease. Constancy of temperature is not so essential in domestic as in refrigerating application, and the small effect on the temperature of a room which occasional opening of double-glazed windows would cause is not comparable with that on the temperature of a small cabinet of only a few cubic feet capacity.

A recent invention consists of a hollow brick formation made of glass which is erected in panels in a manner similar to the laying of bricks. Comparatively large areas of these glass panels may be employed without the heat loss which would accompany the use of plate glass. Their absorption of light is naturally greater, and their use is adapted mainly for halls and stairways and for sundry offices.

Ground Floors.—Improvement in the thermal resistance of the usual boarded ground floor may be effected by several methods. A floor is not exposed to the same increase of air velocity as that to which external walls and windows are subject. Assuming still air conditions, the transmittance is about 0·375 B.Th.U. per sq. ft. per 1° F. per hour for deal boards of 1 in. nominal thickness (**k** = 0·81). Double boarding instead of single gives a reduced figure of 0·262 B.Th.U., while if the second layer of boarding is raised on

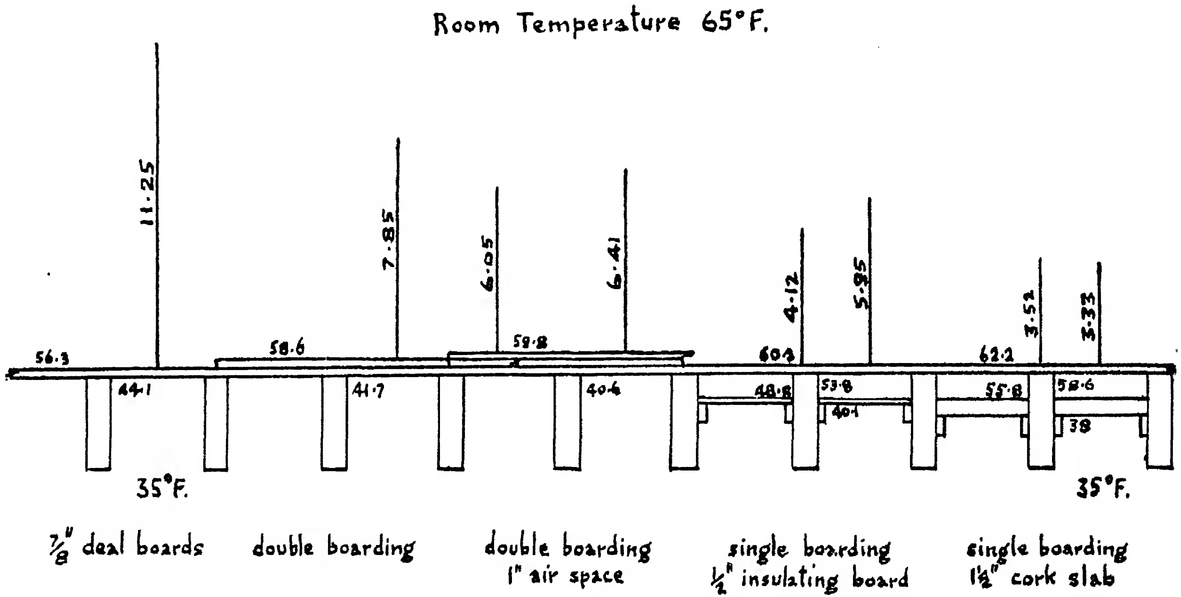


FIG. 22.—INSULATION OF BOARDED FLOORS.

The length of the vertical lines represents the relative heat flow through the particular arrangement. The figures against these lines give the amount of heat flow, at 30° F. temperature-difference, in B.Th.U. per sq. ft. per hour.

battens a further reduction to 0·214 B.Th.U. is available. The cavity formed between the two layers of boarding may be filled with insulating material, subject to the restrictions already mentioned in connection with wall cavities. The improvement resulting from the use of ½-in.-thick insulating board or of 1-in.-thick cork slab laid between the two layers of boarding is a refinement, the cost of which is likely to be justified only under exceptionally disadvantageous circumstances. If insulating material is deemed desirable, it is economical to employ only one thickness of floor boarding and to fix the insulating material between the joists as described below ("Methods of Fixing").

Intermediate Floors.—The insulation of upper floors in dwelling-houses is not often required, since it is usually hoped to maintain the whole building at one temperature. A floor consisting of timber joists boarded on top and covered below with lath and plaster provides a higher thermal resistance, assisted by the cavity, than the usual ground floor in which the joists are exposed on the underside. Where a room is situated above a garage or other office external to the house proper, it may be desirable to insulate the floor. It is simpler and less expensive to effect this by securing insulating material to the underside of the joists than to lay it on top of the floor and so incur the provision of a second floor surface. Insulating board is useful for this purpose and can be plastered or painted. Alternatively, the joists may be boarded on the underside and the spaces between them filled with suitable material. This method gives higher efficiency, but at increased cost.

Top-floor Ceilings.—Ceilings of an upper floor which form a boundary to the attic space under a pitched roof deserve more attention than is usually accorded to them. Mostly consisting of open timber joists, covered on the underside with lime plaster applied either to timber lathing or to

expanded metal, they possess a higher thermal transmittance than is desirable, being about 0·58 B.Th.U. per sq. ft. per 1° F. per hour at 30° F. temperature-difference. If the roof construction is reasonably airtight, the temperature-difference between the air in the room and that in the attic space will not be so great as that through the walls. But against this must be set the fact that the warmed air in the room rises to the ceiling, and that the coldest air in the attic space is in contact with the upper-side. Thus the transfer of heat assists air circulation by thermo-siphon action, which in turn mutually assists heat transfer. Lime plaster is porous to air—visibly so in the case of ceilings which have not been whitened for some time. It is also liable to crack, and unless covered with paper provides the warmed air in the room with a ready means of escape.

So-called plaster board or building board offers a useful means of reducing both porosity and tendency to cracking, and is preferable to lathing, whether of timber or metal. Even with this aid the transmittance is high, and additional means of reducing it are desirable. Again, the formation of a cavity assists the thermal resistance, and this is obtainable by covering the upper-side of the joists. Material in sheet form is the simplest to use, a difficulty sometimes presenting itself with tongued-and-grooved boarding on account of headroom being lost at the eaves. Care is necessary to ensure that all joints between sheets are closed.

Quilt and blanket have been used in positions where only a moderate thermal resistance is necessary. The propensity for moisture absorption to which this type of material is liable, coupled with its attractiveness for vermin, require a retaining construction which is airproof and thoroughly well sealed against atmosphere of high humidity, whether produced artificially from inside or by fog and mist externally. Felted Kapok is available both in blanket form and made up in panels. In the latter form it is usually enclosed in a bitumized paper or similar covering in order to secure

waterproofness. If used in blanket form it may be laid between the ceiling joists, where it is turned on itself two or three times; and sealing against access of moisture-laden air, whether from above or below, is essential.

Methods of Fixing.—A particularly useful method of applying insulating material of slab form to floors and ceilings constructed with timber joists consists in fixing the slabs between the joists. For this purpose the distance between neighbouring joists should equal the width of the slab to be used plus not more than $\frac{1}{8}$ in. for clearance. In the case of cork slab the usual width of slab is 12 in., and with 3-in. timber joists this results in joist centres of $15\frac{1}{8}$ in., which is quite convenient for most buildings of this type. It is an advantage to make use of a standard size of slab if possible, as the edges are machined true and provide a better fit than edges hand-sawn on site. If material of sheet form is to be used, such as insulating board, it is necessary to cut the sheets into suitable strips. For example, 4-ft.-wide sheets can be sawn to give three 16-in.-wide strips, whereas 5-ft.-wide sheets will give four 15-in. strips. Accuracy of spacing is necessary in order to reduce cutting on site to a minimum, and the joists should be spaced with the aid of distance pieces cut accurately to length.

The fixing of the slabs or strips is accomplished by nailing 1-in.-wide timber ribs of any convenient depth on to the sides of the joists. The material is then inserted from the upper-side and rests on these ribs, to which they are lightly nailed. It should be noted that the continuity of the insulating material must not be broken, either by open joints or by the omission of a piece, however small, as this would permit circulation of air from one side of the material to the other, and largely defeat its purpose. Joints between slabs need careful butting and should be sealed after fixing by the use of cement mortar, or by painting the whole of the surface with bituminous paint.

Recessing the insulating material between the joists provides a measure of protection from damage, and is likely to prove more airtight in practice than slabs or sheets laid over joists, the joints of which may be opened by flexure of the comparatively soft material. The slabs may be arranged in contact with either the boarding of a ground floor or the plaster of a light ceiling, but are preferably arranged about 2 in. distant in order to obtain the additional resistance available from a cavity. On the other hand, where plaster is to be used, the placing of the insulating material flush with the joists dispenses with the use of lathing, except for light netting or scrim over the exposed timber joists. Where only a single surface is affixed to joists, the greater thermal resistance of the joists themselves due to their thickness is mainly lost, owing to the free circulation of air over the whole depth of the joists. Increasing the effective thickness of the ceiling or floor regains much of this loss and contributes to the result as a whole.

Timber-framed Huts.—The thermal resistance of simple structures consisting of timber framework, covered on the outside with boarding, asbestos-cement sheets or corrugated

TABLE XIV.—HEAT FLOW OUTWARDS THROUGH WALLS OF TIMBER-FRAMED HUT

(B.Th.U. per sq. ft. per hour. Temp. diff. 25° F., say 55°–30°.)

Outside Lining	With no Inside Lining	With Inside Lining of $\frac{1}{2}$-in Insulating Board ($\mathbf{k}$ = 0·34)
Tongued and grooved Spruce boards $\frac{5}{8}$ in. thick ($\mathbf{k}$ = 0·7)	9·9	5·1
Asbestos-cement sheets $\frac{1}{4}$ in. thick ($\mathbf{k}$ = 8·0)	15·9	6·22
Corrugated iron	16·2	6·27

iron, is provided mainly by the resistance to heat flow offered by the surfaces. In the case of corrugated-iron sheets there is virtually no real contribution to the resistance, owing to the high conductivity and thinness of the material. The addition of a single layer of insulating board ½ in. thick to the inside of the framing, so forming a cavity between the two sheathings, reduces the heat flow as shown in Table XIV.

The figures for heat flow with inside lining presume air-tightness of the cavity.

Concrete Roof Insulation.—The flat concrete roof of a house, hospital, or office building, which is so prominent a feature of modern architecture, is usually lined with a layer of insulating material, the function of which is to impede the flow of heat out of the building in winter, and into the building in summer. The latter is due mainly to the reception of heat by solar radiation, and the temperature-difference to be allowed for varies according to the geographical location of the particular site. In these latitudes the air temperature in contact with the uppermost face of the concrete may be on occasion lower than the desired temperature in the building by 35° F. or more. Increasing importance is being attached to the enhancement of personal comfort and output of work by operatives through the maintenance of agreeable conditions, and in addition a considerable saving can be effected in the amount of fuel consumed by the heating plant. But the most objectionable feature coupled with an uninsulated concrete roof is the condensation of moisture on the under-side when the atmospheric temperature is considerably below that of the building.

Condensation on Ceilings.—The minimum temperature permissible at the lower surface of the concrete to avoid precipitation of moisture is that of the dewpoint corresponding

with the dry-bulb temperature and the relative humidity of the air within the building. The actual temperature of this surface may be calculated from the heat flow for any particular temperature-difference.

The thermal transmission through the uninsulated flat concrete roof of a building in which the temperature is maintained at 65° F. and with an atmospheric temperature of 30° F. is about 13·85 B.Th.U. per sq. ft. per hour. This figure is based on 6-in. thickness of concrete ($\mathbf{k} = 7$), finished on top with $1\frac{1}{4}$-in.-thick asphalt ($\mathbf{k} = 8{\cdot}7$) and underneath with $\frac{1}{2}$-in.-thick plaster ($\mathbf{k} = 3{\cdot}3$), and presumes surface coefficients, with still air, of 1·44 and 1·49 B.Th.U. respectively for the outside and inside surfaces. The temperature of the lower (inside) surface under these conditions will be $\left(65 - \frac{13{\cdot}85}{1{\cdot}49}\right) = 55{\cdot}7°$ F. This temperature is the dewpoint corresponding with 73 per cent. relative humidity of air at 65° F. dry-bulb temperature, and only if the humidity is lower will precipitation of moisture fail to supervene. This degree of relative humidity is exceeded frequently in kitchens and bathrooms where evaporation of water occurs, and may be exceeded also in crowded rooms owing to moisture given off by the human body.

Thermal insulation is employed in order to reduce the rate of heat flow and thereby to raise the surface temperature of the under-side of the roof to a point considerably nearer the dry-bulb temperature of the building. This new surface temperature may be the dewpoint corresponding with relative humidity as high as 90 per cent. at the temperature of the building, and so the probability of condensation becomes remote.

The thickness of insulating material required for this purpose depends upon the temperature-difference and humidity anticipated, and usually ranges from $\frac{1}{2}$-in.-thick insulating board to 2-in. cork slab, both of which materials can be in-cast with mass concrete simply by laying them

on the shuttering prior to pouring the concrete mix. The use of 1-in.-thick cork slab is usually avoided owing to its lack of structural strength and the uncertainty of manipulation without damage. Table XV gives some relative values in the prevention of condensation :—

TABLE XV

(Atmospheric temperature 30° F. Building temperature 65° F. Roof slab : $1\frac{1}{4}$ in. asphalt, 6 in. concrete, **L** in. insulating material, $\frac{1}{2}$ in. plaster.)

Insulating Material	Heat Flow (B.Th.U. per sq. ft. per hour)		Surface Temp. of Ceiling ° F.		Max. Relative Humidity at 65° F. to avoid Condensation. (per cent.)	
	Outside Air :					
	Still	30 m.p.h.	Still	30 m.p.h.	Still	30 m.p.h.
None	13·85	17·9	55·7°	53·3°	73	68
Insulating Board, **L** = $\frac{1}{2}$ in., **k** = 0·34	8·52	10·0	58·9°	58·0°	82	79·5
Cork Slab, **L** = $1\frac{1}{2}$ in., **k** = 0·28	4·32	4·7	61·7°	61·5°	90	89·5
Cork Slab, **L** = 2 in., **k** = 0·28	3·54	3·8	62·3°	62·1°	91·5	91

It is obvious from the figures given in Table XV that the probability of moisture precipitation on uninsulated concrete ceilings is far from being remote in the winter season. In addition, the high thermal transmission enforces a considerable waste of fuel in the maintenance of equable temperature conditions, the cost of which could be diverted to the purchase of insulating material. In the majority of cases this cost is found to be returned in a comparatively short space of time. The latter is emphasized by the low proportion of the calorific value of fuel which is converted

into sensible heat by the average heating arrangements. Another important consideration lies in the rapid fall of interior temperature which results from the high thermal transmission of an uninsulated roof immediately the supply of heat falls off or ceases. On restarting, also, a longer period of time elapses before the normal temperature is regained, and thus generally the temperature control of the building is reduced appreciably from that which is achievable with the aid of insulation.

The figures of Table XV also indicate the considerable effect of wind on structures of low thermal resistance and the stabilizing effect obtained by increasing the resistance (vide Chap. III, p. 64).

Explanation of Fig. 23.

With reference to Fig. 23, if the temperature of the surface of the ceiling were the same as that of the air in contact with it, no condensation would occur. But if the surface temperature is lower than that of the air, condensation may or may not occur, depending upon the difference of temperature and upon the humidity of the contiguous air. The air in immediate contact is cooled by the surface, and if it happens that it is cooled down to its dewpoint, condensation will result. The number of degrees through which the air must be cooled to reach its dewpoint depends upon its initial temperature and humidity. If the percentage humidity is initially low, the air will need to be cooled through many degrees before reaching the dewpoint, but if the humidity is high, only a few degrees of temperature reduction are sufficient.

The graph shown in Fig. 23 is based on an atmospheric temperature of 30° F. with still air.

To find the minimum thermal resistance necessary to avoid condensation at a given temperature and percentage humidity of the air in the building, proceed as follows. Starting at the appropriate Air Temperature on the base line, follow the temperature curve up to the point of intersection with the particular humidity line required, interpolating if necessary. The vertical distance of this point from the base line represents the maximum

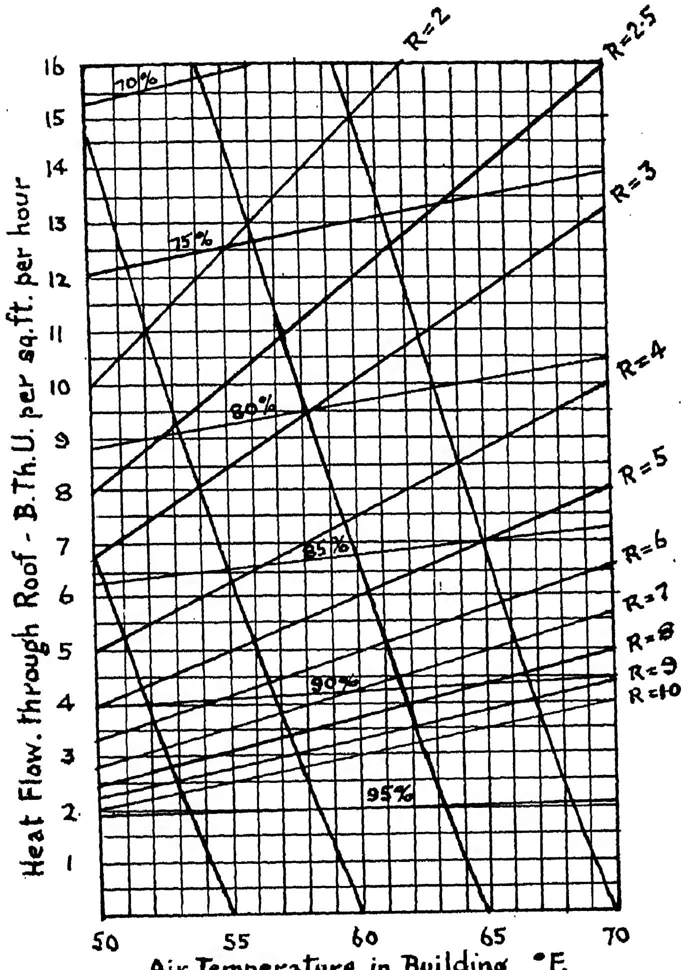


FIG. 23.—CONDENSATION ON CEILINGS

heat flow allowable to avoid condensation, the figures being marked up the left-hand side of the graph. The horizontal distance of this point from the starting-point on the base line represents the maximum number of degrees F. temperature-difference allowable between the ceiling surface and the air to avoid condensation. The actual limiting temperature of the surface can be read off directly on the base temperature scale.

Having thus determined the maximum allowable rate of heat flow, the minimum thermal resistance necessary to prevent it being exceeded is given by the point lying on this horizontal line of heat flow which is vertically above the starting-point on the base line. If necessary, interpolate between the two nearest lines of thermal resistance in order to estimate the value of **R** required.

Referring to Fig. 23, and assuming the building temperature as 65° F., the temperature curve based on 65° F. is found to intersect the 90 per cent. humidity line at 61·7°, i.e. with air of 90 per cent. humidity, condensation will commence with only 3·3° temperature reduction. The outside atmospheric temperature has been taken as 30° F. in building this chart, and with this temperature it is necessary for the heat flow through the roof not to exceed 4·25 B.Th.U. per sq. ft. per hour for the ceiling temperature not to be lower than 61·7°. The necessary thermal resistance to obtain this condition is found by interpolating between the resistance lines **R** = 8 and **R** = 9, and is about 8·1. The thermal resistance of an ordinary concrete roof is rather less than 3, and therefore must be supplemented with that of insulating material to bring the total up to 8·1. If the humidity is 85 per cent. only, the corresponding total resistance necessary is about 5·2. At 75 per cent. humidity the concrete is almost, but not quite, adequate without insulating material at this building temperature.

The "resistance" lines give the total thermal resistance required. By making allowance for the particular building structure, the degree of supplementary insulation is determinable.

BIBLIOGRAPHY

1. Abstracted by permission from British Standard Specification No. 874—1939, *Definitions of Heat Insulating Terms and Methods of Determining Thermal Conductivity and Solar Reflectivity*, official copies of which can be obtained from the British Standards Institution, 28 Victoria Street, London, S.W.1, price 2*s*. 3*d*., post free.
2. *Heat Insulators* (Special Report No. 35, 1929—Food Investigation Board). London, H.M. Stationery Office.
3. *The Transmission of Heat and Gases through, and the Condensation of Moisture on, Wall Materials* (Building Research Special Report No. 4, 1921). London, H.M. Stationery Office.
4. *Lightweight Concrete Aggregates* (Building Research Bulletin No. 15, 1936). London, H.M. Stationery Office.
5. *Heat Transmission* (Building Research Special Report No. 11). London, H.M. Stationery Office.
6. *Thermal Conductivities of Walls, Concretes and Plasters* (Building Research Technical Paper No. 6, 1928). London, H.M. Stationery Office.
7. Ezer Griffiths, "Heat Insulating Materials." *J. of Scientific Instruments*, **15**, No. 4, April, 1938.
8. Ezer Griffiths and J. A. Awbery, "The Thermal Conductivity of Materials used for Solid Carbon Dioxide Containers." 7th Inter. Congress of Refrigeration, 1937.
9. *The Transmission of Heat by Radiation and Convection* (Special Report No. 9, Rev. Ed. 1931—Food Investigation Board). London, H.M. Stationery Office.
10. Langmuir, Meiklejohn and Adams, *Trans. Am. Electrochem. Soc.*, **24** (1913), 54.
11. F. B. Rowley and A. B. Algren, "The Thermal Resistance of Air Spaces," *A.S.H.V.E. Trans.*, **35** (1929), 165.
12. R. E. Watson, *Pyrheliometer Comparisons at Kew Observatory, Richmond.* Meteorological Office, Geophysical Memoir No. 21 (1923).
13. Ezer Griffiths, *Trans. Chem. Eng. Congress* (World Power Conference), 1936, **1**, 366.

14. *The Observatories Year Book*, Meteorological Office, 1937.
15. Ezer Griffiths, " Some Properties of Insulating Materials," *Trans. Brit. Assoc. of Refrigeration*, 1940–41. (A summary bringing up-to-date the information in Special Report No. 35 of the Food Investigation Board entitled *Heat Insulators*, published by H.M. Stationery Office, and now out of print.)

APPENDIX I

Solar Radiation

The *Observatories Year Book* (Meteorological Office, 1937) records observations of Solar Radiation made at Kew (Lat. 51° 28′) and at Eskdalemuir (Lat. 55° 19′) during the year 1935. At Kew the total heat received on a plane normal to the solar beam was recorded by a Gorczynski Pyrheliograph and, in addition, occasional observations were made with an Angström Pyrheliometer. At Eskdalemuir only a Pyrheliometer was used.

The highest daily total recorded by the Pyrheliograph occurred in June and averaged about 237 B.Th.U. per sq. ft. per hour for the daylight hours. The corresponding highest Pyrheliometer result obtained was rather less than 270 B.Th.U. taken at, or shortly after, noon. At Eskdalemuir the Pyrheliometer gave figures of about 305 B.Th.U. on four occasions, only, in the year. The rather lower figures at Kew may be accounted for by obscurity of the atmosphere. The assumption of $\mathbf{Q}_r = 300$ B.Th.U. per sq. ft. per hour as the maximum (Chap. III, p. 69) would seem confirmed as being reasonable.

APPENDIX II

Temperature Test on Flooded Roof of Cold Store during Hot Weather

Building.—180′ 0″ × 50′ 0″ × 28′ 0″ high. One room.
Purpose.—Storage of ice. Approximate load at time of test—3,500 tons.
Roof Construction.—Reinforced concrete 12 in. thick, insulated on top with 6-in. cork slab laid in hot bitumen in two 3-in. layers and covered with $1\frac{1}{4}$-in. rock asphalt.
Depth of water.—2 in. average.
Location.—Latitude 54°, Lancashire.
Time of Tests.—3 p.m. G.M.T.

Date	Wind	Water Temp. ° F.	Air Temp. in contact with Water	Cold Store Air in contact with Roof
June 3rd	N.W. Light	93	75	29
,, 4th	N.E. Very Light	97	73	29
,, 5th	S.E. Very Light	95	70	29
,, 6th	S.W. Light	92	73	29
,, 7th	——	98	71	28·5
	Mean	95	72·4	29

APPENDIX III

Heat Flow through Cylindrical Sections

The equation for radial heat flow through an annular segment, representative of insulating material specially cut to fit pipes and cylindrical columns, is written

$$Q = \frac{k'}{\delta r}.l.2\pi r.\delta t,$$

where r = the radius of the annulus in feet,
l = the length of the cylinder in feet, and
k' = the thermal conductivity referred to 1 ft. as the unit of thickness, i.e. $k' = \frac{k}{12}$

Thus

$$Q.\frac{\delta r}{r} = 2\pi l.\frac{k}{12}.\delta t,$$

whence

$$Q.\log_e r = 2\pi l.\frac{K}{12}t + C.$$

Let r_0 be the outside radius t_0 be the outside surface temperature
r_i ,, inside t_i ,, ,, inside surface temperature

Then

$$Q.\log_e r_0/r_i = 2\pi l.\frac{k}{12}(t_0 - t_i).$$

The outside surface in contact with the atmosphere offers a resistance to heat flow, as for a plane surface. If t_a is the air temperature, then

$$Q = 2\pi r_0.l.f_0(t_a - t_0).$$

Adding these two equations gives

$$\frac{Q}{2\pi l}\left[\frac{12}{k}\log_e r_0/r_i + \frac{1}{r_0 f_0}\right] = (t_a - t_i),$$

and

$$Q = \frac{2\pi l(t_a - t_i)}{\frac{12}{k}.\log_e r_0/r_i + \frac{1}{r_0 f_0}} \text{ B.Th.U. per hour.}$$

The inside temperature, t_i, is that recorded by a thermometer when inserted in the usual pocket in a pipe-line. Omitting 1 from the numerator gives the heat flow per linear foot. Comparison on the basis of 1 sq. ft. of pipe surface is of little interest, except between two pipes of the same bore but with differing thickness of insulation. The real matter at issue is the effect of heat gain (or loss) on the contained fluid. For a given rate of heat flow, this depends on the heat capacity per unit of temperature of the quantity of fluid pumped per hour, which in turn depends upon the velocity of flow and the bore of pipe. The effect of curvature increases greatly for small-bore pipes, and in practice it is not usual for r_0/r_i to be greater than 4.

Cork sectional pipe-covering is the material most widely used for the insulation of low-temperature pipes, and, to a great extent, the thicknesses adopted are limited by the cost of the material. It is not unusual for the thickness to be only one-third of that acceptable for the insulation of the plane surfaces of a building. Consequently, the temperature-gradient is much heavier and the conditions of service more arduous. In the case of a building it is rare for there to be less than 4-in. thickness of insulating material between the plane of freezing-point of water and the outside temperature, but with sectional pipe covering this is sometimes as little as 1 in.

Under such circumstances it is not surprising to find that in practice the useful life of low-temperature pipe insulation is considerably shorter than that of cold rooms themselves; as a whole, it is from one-third to one-half as long. To a minor degree this is due to limitation of space available, but it would seem mainly attributable to the influence of cost. If the insulation "loss" of pipe-lines was of greater relative importance than it is in the thermal scheme, no doubt this condition would not exist, but the anomaly is widespread and often necessitates the replacement of pipe insulation twice, and even three times, in the life of the cold-room with which it is conjoined. In the long run, the total cost is likely to be noticeably greater than the initial cost of efficient insulation would have been, and with this is coupled a lower efficiency of insulation throughout the whole period.

Few are the pipe-line fittings in which even the smallest

amendment of design has been made in order to ensure the efficient application of insulating material. Valve spindles, of necessity, must penetrate the continuity of insulation. An extended gland, to allow room for a sufficient thickness of insulation over the valve body and flanges, would strengthen one of the weakest points in the armour. The addition of a small flange integral with the gland housing, to which insulating material could be secured with a waterproof joint under pressure, would prevent the increscent growth of ice crystals, which, extending between the pipe surface and the insulating material, finally burst the wires retaining the sections. The same effect results wherever discontinuity of the insulation occurs, unless special provision is made. This precipitation and freezing of moisture imposes upon low-temperature pipes a detriment from which hot pipes are immune, and greatly shortens the useful life of the insulation.

TABLE XVI.—HEAT FLOW THROUGH ANNULAR SECTIONS (CALCULATED)

(B.Th.U. per 1° F. per lin. ft. per hour.)

Cork $k = 0{\cdot}34$ Thickness $(r_0 - r_i)$ in.	Outside diameter of pipe, $2r_i$ (inches)					
	$6\frac{1}{2}$	$5\frac{1}{2}$	$4\frac{1}{2}$	$3\frac{1}{2}$	$2\frac{3}{8}$	$1\frac{5}{16}$
4	0·212	0·19	0·168	0·146	—	—
3	0·255	0·226	0·198	0·169	0·134	—
2	0·335	0·295	0·253	0·213	0·166	0·119
$1\frac{1}{2}$	0·406	0·355	0·302	0·252	0·194	0·135
1	0·538	0·472	0·393	0·323	0·243	0·163

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